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Technical Note

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By J. Dummer


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# Instantaneous Morison Equation Force Coefficients Computation

**ABSTRACT** This research hypothesized that the use of conventional time invariant drag and inertia coefficients in the Morison equation for dynamic wave force simulation is incorrect. These coefficients are obtained via period averaging regression analysis techniques that efface the subperiodic fluctuations in the flow and pressure fields adjacent to structural members. Computer programs were written to develop a set of instantaneous drag and inertia coefficients for use in conjunction with the Morison equation to retain this subperiodic information. The results of this effort are inconclusive due to the computation of some negative instantaneous drag coefficients from ostensibly reliable well conditioned wave force experimental data.

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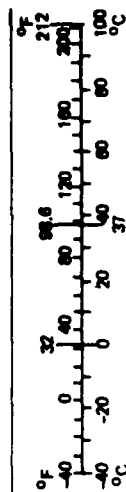
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
in ft yd mi	inches	2.5	centimeters	cm
	feet	30	centimeters	cm
	yards	0.9	meters	m
	miles	1.6	kilometers	km
in <sup>2</sup> ft <sup>2</sup> yd <sup>2</sup> mi <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
	square feet	0.09	square meters	m <sup>2</sup>
	square yards	0.8	square meters	m <sup>2</sup>
	square miles	2.6	square kilometers	km <sup>2</sup>
	acres	0.4	hectares	ha
oz lb	ounces	28	grams	g
	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
tsp Tbsp fl oz c pt qt gal ft <sup>3</sup> yd <sup>3</sup>	teaspoons	5	milliliters	ml
	tablespoons	15	milliliters	ml
	fluid ounces	30	milliliters	ml
	cups	0.24	liters	l
	pints	0.47	liters	l
	quarts	0.95	liters	l
	gallons	3.8	liters	l
	cubic feet	0.03	cubic meters	m <sup>3</sup>
	cubic yards	0.76	cubic meters	m <sup>3</sup>
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
mm cm m km	millimeters	0.04	inches	in
	centimeters	0.4	inches	in
	meters	3.3	feet	ft
	kilometers	1.1	yards	yd
cm <sup>2</sup> m <sup>2</sup> km <sup>2</sup> ha	square centimeters	0.16	square inches	in <sup>2</sup>
	square meters	1.2	square yards	yd <sup>2</sup>
	square kilometers	0.4	square miles	mi <sup>2</sup>
	hectares (10,000 m <sup>2</sup> )	2.5	acres	
g kg t	grams	0.035	ounces	oz
	kilograms	2.2	pounds	lb
	tonnes (1,000 kg)	1.1	short tons	
ml l l l m <sup>3</sup> m <sup>3</sup>	milliliters	0.03	fluid ounces	fl oz
	liters	2.1	pints	pt
	liters	1.06	quarts	qt
	liters	0.26	gallons	gal
	cubic meters	36	cubic feet	ft <sup>3</sup>
	cubic meters	1.3	cubic yards	yd <sup>3</sup>
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



\*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Mon. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10-286.

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## EXECUTIVE SUMMARY

The intent of this research effort was to enhance the design engineer's capability to predict wave-induced hydrodynamic loads for given wave conditions. This research hypothesized that the use of conventional period averaged, time invariant, drag and inertia coefficients in the Morison equation wave force prediction model is incorrect. These constant coefficients efface the subperiodic fluctuations in the flow and pressure fields in the near vicinity of the structure due to the vortex shedding or other unsteady hydrodynamic phenomena. Consequently, it was proposed that a set of instantaneous wave force coefficients be developed (for use in conjunction with the Morison equation) that would account for these subperiodic fluctuations.

A computer program was written to analyze wave force experimental data and yield the instantaneous drag and inertia coefficients. This was accomplished by employing the Morison equation at two points within the wave force data set that are separated by a small time interval. Since the wave force and water particle velocities were measured at the two points, and since the water particle acceleration can be computed to first order accuracy at both points, all of the Morison equation variables are known except for the drag and inertia coefficients. If it is assumed that these force coefficients remain constant over the small time interval, then a solvable system of two equations and two unknowns is achieved.

The results of this research have been inconclusive due to the computation of some instantaneous negative drag coefficients from ostensibly reliable, well conditioned data. Since the force coefficients are scalar quantities, negative coefficient values are not physically relevant. This invalid result occurs in data records in which the numerical acceleration is very nearly in phase with the measured force and hence, the drag force is not contributing to the total force despite significant measured velocities. This may occur because: (1) the numerically computed acceleration is incorrect, (2) the measured wave force data records were inadvertently phase shifted, (3) the Morison equation wave force model is inappropriate on an instantaneous basis, or (4) the wave induced velocities measured in the wave flow field drastically differ from the velocities immediately adjacent to the cylinder.

It is therefore concluded that:

1. The validity of instantaneous Morison equation wave force coefficients is still unknown.
2. This effort should be repeated with another wave force data set to see if negative force coefficients are generated again.
3. Future laboratory or ocean wave force experiments must be conducted with an instrumentation system that demonstrates that all electronically recorded data records are phase locked.

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## INTRODUCTION

Navy utilization of fixed and floating space-frame ocean structures has increased during recent years. Existing and proposed facilities, such as the Atlantic Coast Maneuvering Range (ACMR) towers, Tactical Air Combat Training System (TACTS) platforms, Elevated Causeway (ELCAS) cargo offloading facilities, Undersea Surveillance Sensor Arrays, etc., are a few examples. All of these facilities must withstand ocean environmental loadings due to waves, wind, ice, earthquakes, etc. In order to design these structures to withstand the various imposed environmental loads, Navy design engineers must first have a means to quantify the magnitudes of the design loads. For structures that respond dynamically, the design engineers must be able to specify the temporal fluctuations of the load as well as the magnitudes. That is, in order to calculate the dynamic structural response, they must be able to predict the applied force history for a given set of environmental conditions. The intent of this research effort is to enhance the design engineer's capability to predict wave-induced hydrodynamic loads for given wave conditions.

References 1 and 2 have demonstrated the Navy requirement for a design-oriented wave force model that will produce reliable and yet economically feasible offshore structures. Necessarily, such a model must represent the complex physical phenomena of a fully turbulent time-dependent flow field about a bluff body and be tractable for designers. To date, no such model has been proposed, nor is it likely that a model satisfying the dichotomy of simple analytical format for complex fully turbulent flows will be discovered in the near future. Considerable research effort in basic fluid dynamics will be required in order to achieve this goal. Morison and others (Ref 3), influenced by Stokes (Ref 4), have provided the first iteration of this process with the well-known "Morison equation." This equation is a semi-empirical model

in which the wave force is evaluated per unit length of the structural member as the sum of a drag force term and an inertial force term.

Typically the Morison equation is written as:

$$F = \frac{C_D}{2} \rho D U |U| + \frac{C_M}{4} \rho \pi D^2 \dot{U} \quad (1)$$

where:  $F$  = force per unit length. This model may yield the maximum design load or the temporarily variant force depending upon whether the kinematics values are fixed or varied as a function of time.

$C_D$  = drag coefficient

$\rho$  = water mass density

$D$  = pile (or structural member) diameter

$U$  = horizontal orbital fluid velocity component

$C_M$  = inertia coefficient

$\dot{U}$  = horizontal orbital fluid acceleration component. Generally, only the local accelerative component of the total horizontal acceleration is used.

Since its inception, the basic Morison equation has gained considerable reputation. It has been used to successfully design many offshore structures. This success must be partially attributed to required safety factors due to uncertainties inherent in the wave force loading analysis procedures (e.g., determination of a design wave, force coefficient selection, estimation of current effects, estimation of roughness effects, etc.). Indeed, several investigators (Ref 1, 2, and 5 through 9) have noted a discrepancy between measured wave forces and those predicted via



Morison equation techniques. Figure 1 provides an example of this discrepancy for an idealized laboratory wave. This error becomes more significant when considering the dynamic analysis necessary for deepwater structures. That is, in order to accurately model the dynamic response of the structure, the designer must be able to accurately represent the wave-induced hydrodynamic component of the dynamic forcing function for all values of time.

In order to gain a better understanding of why these errors occur, it is informative to examine the individual variables required in order to employ the Morison equation (Equation 1). The pile diameter and water mass density are easily determined and require no further discussion. The horizontal components of orbital fluid velocity and acceleration are commonly referred to as the water particle kinematics. The water particle kinematics are determined analytically by an appropriate wave theory. Selection of the wave theory is principally based on the geometric characteristics of the wave and the water depth. Finally, the force coefficients (coefficient of inertia and coefficient of drag) are empirically determined. There is a limited availability of design curves for the selection of the force coefficients. Furthermore, the available force coefficient data exhibit considerable scatter. Figure 2 shows a compilation of laboratory drag coefficient data published by Wiegel in 1964 (Ref 10). Figure 3 shows the drag coefficient data from the Exxon Ocean Test Structure experiment published by Heideman, Olsen and Johansson in 1979 (Ref 11). Both figures exhibit a great deal of scatter with relatively little improvement in Figure 3 despite a 15-year time lapse. It is apparent from Figure 3 that for the drag-dominated flow condition of Keulgan-Carpenter number ( $UT/D$ ) equal to forty, the predicted wave loads would vary by almost 40 percent due to the scatter in the drag coefficient values.

In order to more completely understand this problem, it is necessary to examine the role of the force coefficients in the Morison equation (Equation 1). As with all coefficients, the purpose of the force coefficients is to quantify the individual force terms. That is, the drag coefficient transforms the product of the flow energy, or strength ( $u|u|$ ), the fluid density ( $\rho$ ), and a measure of the structural obstruction ( $D$ )

into a quantified form drag force. This form drag force arises from the high-low pressure gradient across the cylinder due to the fluid viscous effects of flow separation and wake generation. The drag coefficient must supply information regarding the integration of a complicated pressure field in a rotational flow situation. This information is not supplied by the other flow field, fluid, or structural geometry variables.

Similarly, the inertial coefficient transforms the product of the fluid acceleration, the displaced volume of fluid, and the fluid density into a quantified inertial force. This inertial force is due to the pressure gradient that would have accelerated the fluid in the absence of the structure and the additional energy extracted from the flow field due to presence of the structure. Hence, both of the Morison equation force coefficients are tasked to supply information regarding complicated flow field interaction with a structural member. This information is supplemental to that given by the kinematic, geometric, and fluid variables in the Morison equation.

Although both the theoretical kinematics and the force coefficients are known to contribute to errors in the predicted wave force, this research has only addressed the problems associated with the force coefficient selection. It is known that the force coefficients are a function of certain physical characteristics of the cylinder and of the flow field. Unfortunately, a complete understanding of the influence these characteristics have on the force coefficients is lacking. However, efforts have been made to consolidate some of the physical characteristics into dimensionless parameters. The two principal dimensionless parameters are the Keulegan-Carpenter number and the Reynolds number. For completeness, the following descriptions of these parameters are provided:

Keulegan-Carpenter number (K):

$$K = \frac{U T}{D}$$

where: U = water particle velocity

T = wave period

D = cylinder diameter

Reynolds number (Re):

$$Re = \frac{U D}{\nu}$$

where:  $\nu$  = fluid kinematic viscosity

Physically the Keulegan-Carpenter number, K, is proportional to the ratio of the horizontal distance traveled by a water particle during a wave cycle divided by the diameter of the cylinder. This provides a measure of whether inertial or viscous effects dominate the fluid-structure interaction. That is, for small K the water particles do not travel very far relative to the cylinder diameter. Since the water particles don't move very far past the cylinder, both flow separation and wake generation effects are reduced or effectively eliminated. Consequently, accelerative (inertial) effects are predominant for small K values. For large K the water particles travel large distances past the cylinder. This tends asymptotically toward steady flow conditions in which the viscous effects of flow separation and wake generation predominate. Hence wave flows with high K values are drag dominated.

The Reynolds number, R, is the ratio of the inertial forces to the viscous forces and yields information regarding the turbulent intensity of the local flow field. Reynolds numbers of interest for ocean design conditions are generally in the  $10^5$  to  $10^7$  orders of magnitude. Reynolds numbers obtained in laboratory model studies are in the  $10^3$  to  $10^5$  orders of magnitude. Hence, exact modeling similitude in existing laboratories is not possible.

The scatter in the Morison equation force coefficients when plotted as a function of K and R indicates that these two dimensionless parameters are inadequate to specify the functional dependency of the force coefficients. It has been stated above that the force coefficients are functions of the flow field interaction with the structural member. This interaction varies throughout the wave cycle as the water particle kinematics and the local pressure field vary. The parameters R and K, on the other hand, are generally computed using the maximum value of the horizontal component of the orbital fluid velocity. Hence, they provide

flow field information for the parameterization of the force coefficients relative to one time during the wave cycle. It is hypothesized that this is insufficient to fully characterize the temporally dependent flow field and provide functional parameterization of the force coefficients. This research has proposed more effective means of parameterization of the force coefficients that account for the variation of the flow field during the wave cycle.

As stated above, excessive scatter exists in the published data for the Morison equation force coefficients. As a consequence, considerable variation in predicted design wave forces may be realized for similar environmental conditions. A portion of this problem may be attributed to the inability of R and K to fully parameterize the force coefficients over the temporally variant flow cycle. This problem is compounded by the conventional methods of establishing the force coefficients from experimental data. Generally, Fourier averaging or least squares error minimization regression analysis techniques have been employed. These techniques yield constant, averaged values of the force coefficients by finding the particular coefficient values which minimize the errors between the predicted wave force and the measured experimental wave force over a wave period. That is, they provide coefficients which are rendered constant over the wave period via an averaging process. This averaging process effaces the subperiodic temporal variation in the force coefficients which occur during the wave cycle. These temporal variations occur due to the variations in the local flow and pressure fields throughout the wave cycle that are not accounted for by the Morison equation kinematics. As a consequence, conventional period averaged force coefficients cannot provide the subperiodic temporal dependency necessary for the Morison equation to perform as an accurate dynamic wave force model.

Keulegan and Carpenter (Ref 12) recognized that the use of period averaged constant force coefficient values in the Morison equation led to errors in the prediction of the dynamic force. They noted that this error, or residue, could be decomposed in a Fourier series and that "local" values of the force coefficients could be obtained as a function of the wave phase and the Fourier coefficients.

Sarpkaya (Ref 13) noted that the technique employed by Keulegan and Carpenter was not strictly correct since it assumed that there is no distinction between the accelerating and decelerating phases of the flow. Sarpkaya (Refs 5 and 13) proposed that the coefficients be assumed to be constant over some small increment of the wave phase. This allows the force coefficients solution by employing the Morison equation at both ends of the phase interval. Sarpkaya's (Ref 13) research verified that indeed the instantaneous force coefficients varied significantly during the wave cycle. This research employs the technique proposed by Sarpkaya to develop an instantaneous wave force coefficient set. In order to accomplish this, however, it is necessary to have high quality wave force experimental data. These data should be obtained under carefully controlled conditions in order to insure the accuracy of the wave force measurements. The experimental scale should (preferably) approximate design scales to maintain appropriate hydrodynamic modeling similitude. Furthermore, to avoid uncertainties associated with kinematics values obtained via predictive wave theories, the water particle velocities should be measured simultaneously in near proximity to the wave force measurements.

In accordance with all of the above, the tasks undertaken by this research were threefold:

1. Locate an acceptable wave force experiment that satisfies the criteria of high quality wave kinematics and force measurements. The data from this experiment must be data-base-managed into an acceptable format for a time domain solution of instantaneous wave force coefficients.
2. Develop a high speed numerical algorithm that processes the experimental data in the time domain to yield instantaneous drag and inertia coefficients for the Morison equation.
3. Develop appropriate dimensionless parameters and post-process the force coefficients into a matrix configuration data base. The data base must be appropriately organized using the developed dimensionless

parameters so that the designer can retrieve the necessary instantaneous force coefficients given the appropriate fluid, flow field, and structural variables comprising the dimensionless parameters.

Tasks 1 and 2 have been accomplished using the Oregon State University wave force experimental data set described in Reference 14. However, significant problems have arisen in the computation of negative drag coefficients for some of the data set analyzed. Task 3 has not been completed due to the problems encountered with Tasks 1 and 2. However, additional dimensionless parameters for the parameterization of the instantaneous force coefficients have been developed. Documentation of the work accomplished on each of these tasks is provided in the succeeding sections.

## ACCOMPLISHMENTS

### TASK 1

As discussed previously, the Oregon State University wave force experimental data set for a 12-inch-diameter vertical cylinder was employed in this research effort. This data set was used because it obtained ostensibly high quality measurements of:

1. Local and total dynamic in-line and transverse wave forces
2. Vertical and horizontal water particle velocities
3. Circumferential local pressure field around the cylinder
4. Water surface profile

The data were recorded at a sampling rate of 256 data points per wave period for each of the measured variables. Hence, the data acquisition rate is well above the hydrodynamic fluctuation rate and the data set is well suited for the instantaneous force coefficient analysis.

In addition, this experiment was conducted at a scale that models real ocean conditions as closely as possible in a laboratory. Reynolds numbers in excess of  $2 \times 10^5$  were achieved and the Keulegan-Carpenter number ranged from 2 to 17.

The data were recorded for a broad range of wave conditions and a large number of waves for each given condition. Hence it is possible to examine cycle-to-cycle wave force variations for what appears to be identical waves. Due to the bulk of this data set, it is possible to compute force coefficients for widely varying hydrodynamic conditions. As a consequence of the various variables measured, it was hoped that these coefficients could be effectively parameterized to develop a matrix configuration force coefficient data base which would have relevance to some ocean design conditions. A complete description of the experiment, the data, and the data acquisition procedures is provided in Reference 14.

#### **PREPROS**

A preprocessor computer program, PREPROS, has been written to organize and condition the raw experimental data for processing by the force coefficient analysis program. PREPROS has been written as a main program and a series of subroutines. The function of the main program is to read the raw experimental data and user defined directives, define common block data, call the various subroutines to perform the various data conditioning and organization tasks, and write the processed data on output files for user examination and processing by the force coefficient analysis program. A flow chart for the major activities performed by PREPROS and its attendant subroutines is provided in Figure 4.

PREPROS creates two output files. The first output file always has the file name "OSU.OUT". This file is primarily an echo of the input experimental data and derived or computed data such as The Fast Fourier Transform coefficients, numerically derived horizontal water particle acceleration time history, wave heights, wave periods, maximum/minimum measured horizontal and vertical water particle velocities, horizontal hydrodynamic measured wave force time history for each wave in an experimental run, vortex shedding periods, etc. OSU.OUT is primarily intended to provide the user with a sufficient amount of input and computed data

in order to ascertain that PREPROS is correctly processing the input data for later use by the instantaneous coefficient processing program, "COEFFJD". In order to facilitate this subsequent processing, PREPROS organizes a second output file to be read as input by COEFFJD. This second output file has a variable filename which is determined by the experimental run designator information read on the header of the experimental data file and is stored in the variable address called "RUNID". For example, the output file name "T46H43.012" would be stored in the RUNID variable for an experimental data set for experimental run number 12 comprised of multiple monochromatic waves with target wave periods of approximately 4.6 seconds and target wave heights of 4.3 feet. When PREPROS has completed the analysis and processing of the run 12 experimental data set, the user will find the files OSU.OUT and T46H43.012 on the user's disk file directory. Pending the user's review and approval of OSU.OUT, T46H43.012 would be ready for instantaneous force coefficient processing by COEFFJD.

The following numbered descriptions summarize the major computational, directive, and input/output (I/O) activities performed by PREPROS as shown on Figure 4:

1. **INTERACTIVE I/O:** User specifies an existing experimental data file (in the user's directory) to be processed by PREPROS. This could be an OSU experimental data file or any other data file in the appropriate format.

2. **READ/ECHO:** PREPROS reads the header on the data file to obtain the: (1) Name of the file to be created for instantaneous force coefficient processing by COEFFJD and stores this in the variable address called RUNID. (2) Target wave period, T. (3) Target wave height, H. (4) Number of data channels, NCH (always 5 for OSU data). (5) Number of data points in each data channel, NPTS (always 2048 for OSU data). This information is echoed onto the user's terminal and the OSU.OUT file.



3. **READ/ECHO:** PREPROS reads the time history data records into the array X(a,2048) where "a" is: (1) Water surface profile record - ft. (2) Vertical water particle velocity component - ft/sec. (3) Horizontal water particle velocity component - ft/sec. (4) Transverse force record measured by the local force transducer - lb. (5) In-line force record measured by the local force transducer - lb. This data is echoed onto the OSU.OUT (and later onto RUNID variable) output file.

4. **CALL SUBROUTINE "ZERO":** PREPROS calls subroutine ZERO to examine the water surface profile time history data (array, X(1,2048)). The data array contains up to 10 monochromatic waves. Subroutine ZERO defines individual waves within the data record using a zero upcrossing technique to define the beginning and end points of each individual wave. This subroutine also computes the wave period for each of the waves by subtracting the number of the wave beginning data point from the end point and multiplying by the digitization interval. The definition of individual waves and their associated wave periods within the data record is required information for a wave-by-wave analysis of the experimental data. This information is written to the OSU.OUT (and later onto the RUNID variable) output file.

5. **CALL SUBROUTINE "MAXIMUM":** PREPROS calls subroutine MAXIMUM to examine the water surface profile data array, X(1,2048), the vertical water particle velocity data array, X(2,2048), the horizontal water particle velocity data array X(3,2048) and the in-line force data array X(5,2048). This subroutine finds the maximum and minimum horizontal and vertical water particle velocity for each individual wave defined in Subroutine ZERO. It also computes the wave height and the maximum and minimum in-line force for each wave. The largest (absolute) value of the maximum and minimum values determined is retained as an absolute maximum value. These absolute maximum values of the horizontal and vertical velocity components, the measured in-line force, and the wave height are thought to be important information for the parameterization of the force coefficients. In addition, since the Oregon State Experiments were conducted in a closed wave flume, a return current is established to offset the nonlinear effects of mass transport. Subroutine MAXIMUM

computes the magnitude of this return current by averaging the horizontal water particle velocity data over the wave period. All of the above described information determined by MAXIMUM is written to the OSU.OUT (and later to the RUNID variable) output file.

6. **CALL SUBROUTINE "ACCEL"**: PREPROS calls subroutine ACCEL to compute the numerical derivative of the horizontal water particle velocity data array to yield the horizontal water particle acceleration time history. Examination of Equation 1 reveals that these acceleration values are necessary in order to quantify the inertial force term in the Morison equation. Unfortunately, there are no direct measurement techniques for determining the water particle accelerations and, hence, a numerical differentiation algorithm such as this must be employed to obtain the requisite acceleration record. ACCEL accomplishes this by employing the Fast Fourier Transform (FFT) technique to transform the time domain measured horizontal velocity record into a frequency domain velocity spectrum. Since this essentially equates the original time series to a sine and cosine series in the frequency domain, it is apparent that the numerical derivative is easily computed by multiplying each term in the sine and cosine series by its respective angular frequency, changing the sine to a cosine, and the cosine to a minus sine function. However, the multiplication by the respective angular frequency at the higher harmonics tends to artificially increase the noise level. This can be observed in Figures 5 and 6. Figure 5 represents the amplitude spectrum obtained from the measured velocity record for a wave with approximately a 2.5 second period (0.4 Hz). It can be seen that the largest spectral amplitude does indeed correspond with the fundamental frequency and very little energy (except for a small spike at the third harmonic) is exhibited at other frequencies. Figure 6 shows the acceleration spectrum for the same wave which has been filtered (FFT coefficients artificially set equal to zero) at frequencies above 1.5 Hz. Note, however, that the relatively small spectral amplitudes from 1.0 to 1.5 Hz in Figure 5 have been drastically increased in Figure 6. If the small spectral amplitudes in Figure 5 correspond to electronic noise, it is easy to see how this noise is progressively amplified in the acceleration spectrum as

the frequencies increase by the numerical differentiation process. Consequently, it is necessary to devise some method to filter the noise from the velocity record before computing the acceleration record.

Unfortunately, filtering noise is, at best, a magical art. This is due to the fact that low level true signals are impossible to distinguish from noise. Heavy filtering will reduce the noise amplification but will also efface the subperiodic (high frequency) signal which may be due to important phenomena such as vortex shedding. Light filtering preserves the subperiodic signals but effaces these true signals via noise amplification. This quandry has plagued this research since it relies on high quality instantaneous (or subperiodic time scale) data records to achieve high quality instantaneous force coefficients.

Originally, ACCEL allowed the user to specify a filter frequency. At frequencies above the user specified frequency, all of the FFT coefficients in the spectrum were set equal to zero. In Figure 6, for example, all of the FFT amplitude coefficients have been zeroed at frequencies greater than 1.5 Hz. Note, however, in Figure 6 that this still produced amplification of spectral amplitudes which probably were due to electronic noise. It could be argued that a lower frequency, say 0.8 Hz, might have done better. This would have resulted in zeroing the third harmonic amplitude (1.2 Hz) which may be a real signal. It may then be argued that only the harmonic frequencies should be retained. ACCEL has been rewritten to use only the harmonic frequencies.\* Questions as to how many harmonics to retain can be answered partially by comparing the variance values. It has been found that by using only the first two harmonics almost all of the time history/spectral information is preserved in the OSU data. Questions regarding how much information of a nonharmonic nature (such as that due to vortex shedding and wake interaction) is lost remain open for speculation. The user should also

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\*The ACCEL subroutine statements that allow a user defined filter frequency have not been deleted. They have been "commented" to inactive status with a "C 9/10/86" comment designator. They can be reactivated by removing the comment designator and deleting the harmonic filter statements.

be wary of cases in which the actual wave frequency is not closely approximated by one of the digital FFT frequencies (based upon the digitization interval). This will cause amplitude leakage to the digital spectral frequencies on either side of the actual frequency. Fortunately the OSU monochromatic waves being analyzed have frequencies close to the target wave frequency and hence the digitization interval yields FFT frequencies which closely approximate the actual wave frequencies. This may not be the case for other data sets or for the analysis of individual random waves.

One other issue that the user should be aware of involves the use of the variance values to verify that a derived spectrum and a data record are roughly equivalent. Generally speaking, if the variances match the two are equivalent. In fact, in going from the time domain to the frequency domain or vice versa ACCEL will abort the program execution if the variances don't closely match. However, the fact that the variance of the velocity data record is closely approximated by the variance of a filtered velocity spectrum does not indicate that the filtered velocity achieved by the inverse FFT will closely approximate the original velocity record at all points in time. That is, since the variance is a kind of cumulating/averaging indicator, it tells the user that, on the average, there will be a good correspondence over the entire record with the possibility of localized deviations. To verify this a sensitivity study was conducted in which a velocity record was FFT'ed to the frequency domain. The resulting spectrum was then filtered at various different frequencies and the filtered spectrums were inverse FFT'ed back into time histories. These time histories were then compared data point by data point to the original velocity record to determine the local normalized error via the equation:

$$\text{error}(i) = \frac{U_m(i) - U_f(i)}{U_m(i)} \quad (2)$$

where:  $U_m(i)$  = the  $i^{\text{th}}$  value of the measured velocity record

$U_f(i)$  = the  $i^{\text{th}}$  value of the filtered velocity record

The average error was also computed over the entire record by the equation:

$$\text{average error} = \frac{\sum_{i=1}^N |\text{error}(i)|}{N} \quad (3)$$

where: N = total number of data points

Table 1 shows the average error from Equation 3 converted to percentages for the indicated filter frequency. Note that the target monochromatic wave frequency for this analysis was approximately 0.22 Hz so that the data in Table 1 with filter frequencies greater than 0.44 Hz retained at least the first two harmonics. Hence the variances approximately matched for filter frequencies greater than 0.44 Hz.

Table 1. Average Record Errors For Measured Velocities Versus Filtered Velocities for Approximately 0.22-Hz Monochromatic Waves

Filter Freq. (Hz)	27.5	17.5	10.0	5.0	2.0	1.5	1.0	0.5	0.44	0.22
Avg. Error (%)	0.007	0.007	0.007	0.007	0.007	0.008	7.5	19.9	21.1	49.3

Despite the fact that the variances might match, Table 1 shows that the record averaged error can be significant when heavy filtering is conducted (i.e., filtering all FFT coefficients above 1.0, 0.5, 0.44, or 0.22 Hz). It should be noted that most of the errors for the 1.0, 0.5 and 0.44 Hz cases occurred and accumulated as the measured velocity tended to go to zero. At these points the accuracy of the measured velocity is also questionable. The questionable accuracy of the velocity measurements and the filtered velocity as the velocity tends toward zero leads to additional theoretical questions with regard to the numerical generation of an accurate acceleration record. This is due to the fact that wave theories indicate that the acceleration should tend either to maximum or minimum values as the velocity tends toward zero. Consequently, if the

veracity of the velocity record is questionable near zero, it may be argued that numerically derived accelerations at their most important parts, maximum or minimums, are also questionable.

As stated above, questions have plagued the numerical generation of the acceleration record in this research project. They are documented here in order for future research to address and/or solve.

In summary, subroutine ACCEL computes the variance of the horizontal velocity data array, X(3,2048), and then calls subroutine "FFT" to transform it into the frequency domain. The variance of the velocity spectrum is then computed and compared to the variance computed for the data array. The two variances must approximately match. If they don't the PREPROS program execution is aborted. The velocity spectrum is then filtered by zeroing all of the FFT coefficients except for the first and second harmonics. For the OSU data this requires that only the 9<sup>th</sup>, 17<sup>th</sup>, 2033<sup>rd</sup>, and 2041<sup>st</sup> coefficients are retained. The variance for the filtered velocity spectrum is then computed and compared to the variance computed for the velocity data array. If these two variances don't approximately match, a user warning is printed at the terminal. ACCEL then computes the acceleration spectrum by multiplying the remaining FFT coefficients by their respective angular frequency, reversing the real and imaginary parts of the FFT coefficient and changing the algebraic sign of the cosine coefficients (originally the real part). The variance of the acceleration is computed and ACCEL calls the FFT subroutine to inverse transform the acceleration spectrum to an acceleration time history. Once again, the variance of the acceleration time history is compared to that of the acceleration spectrum. They must be approximately equal or the program will abort. The average acceleration value for the acceleration time history is also computed. It must be approximately zero or a warning is printed on the terminal screen. Finally the acceleration time history is written to the data array X(6,2048) and the OSU.OUT (and later the RUNID variable) output file.

The subroutine FFT computes the forward or inverse fast Fourier transform for any time series,  $g(t)$ , based on:

$$g(t) = \frac{1}{2} \sum_{n=1}^N C_n \exp(-i\omega_n t)$$

where:  $C_n$  = complex Fourier coefficients

$\omega_n$  = angular frequency components

$i = -1$

7. **INTERACTIVE I/O:** PREPROS asks the user for the pile diameter, the length of the test section, and the mass density of water. For the OSU data the input would be 1.0, 1.0, 1.94 corresponding to 1-foot-diameter, 1-foot-long local force transducer in water having a density of 1.94 slugs/ft<sup>3</sup>.

8. **OPEN OUTPUT FILE:** PREPROS opens the output file designated by the variable name stored in the RUNID address. This file will be used as input for the instantaneous force coefficient processor program, COEFFJD.

9. **CALL SUBROUTINE "RAINFLOW":** PREPROS calls RAINFLOW to examine the transverse force data array, X(4,2048). This subroutine locates the relative maxima and minima (i.e., peaks and valleys) in the transverse force record using a modification of the technique employed in the commercial RAINFLOW program. The peaks and valleys in the transverse force record are caused by transverse pressure gradients across the cylinder. These pressure gradients are due to vortex formation, shedding, and wake interaction with the test pile. RAINFLOW computes the vortex shedding time by determining the time interval between the transverse force peaks. Since relative maxima and minima are encountered in the transverse force record, a peak-to-peak, or valley-to-valley, time increment technique is required. Hence it was not possible to use subroutine ZERO to perform this effort. The number of vortices shed, the beginning and ending data

point numbers, and the vortex shedding periods are written to the OSU.OUT and RUNID variable output files. This information is useful for the parameterization of the force coefficients. It provides some quantification of the variation in the dynamic pressure field about the cylinder due to vortex shedding and wake interaction. It has been hypothesized that accurate quantification of the force coefficients must account for these temporal fluctuations in the pressure field. However, it is unknown what magnitudes of these fluctuations are hydrodynamically meaningful. That is, the small variations in the pressure field due to, for example, third generation vortices being washed back over the cylinder may have little effect on the force coefficients. Considerable effort is required in order to derive a meaningful coefficient parameter from the vortex shedding periods.

10. **WRITE OUTPUT TO RUNID FILE:** The data generated by PREPROS which will be required by the instantaneous coefficient processor program, COEFFJD, is written to the RUNID variable output file.

11. **MORE PREPROCESSING:** PREPROS wants to do more and will ask the user for another experimental data file to process. In order to stop PREPROS, hit a "Return" when prompted for the new experimental data file.

#### **PREPROS Summary**

In summary, PREPROS is a preprocessor computer program which, by virtue of its subroutine elements, performs the following useful functions necessary for subsequent determination of the force coefficients:

1. Reads and organizes the raw experimental data.
2. Subdivides the continuous data recording into individual wave increments.



3. Determines the maximum horizontal and vertical water particle velocities, the wave height, and the average return current for each wave.
4. Computes the horizontal water particle acceleration from the measured velocity.
5. Performs the forward and inverse fast Fourier transforms of any user specified data record.
6. Numerically filters any specified data record by truncating the Fourier series at a user directed frequency.
7. Analyzes the transverse force record to determine the time interval between dynamic pressure fluctuations due to vortex shedding and wake interaction.
8. Creates a data file for analysis by the force coefficient processor program.

## **TASK 2**

As previously stated, Task 2 required the development of a computer program that would read and analyze the processed data from PREPROS and compute the instantaneous drag and inertia coefficients for the Morison equation (Equation 1).

### **COEFFJD Computer Program**

The computer program "COEFFJD" has been written to accomplish the task stated above. The theory employed is shown in Figure 7. Essentially, the Morison equation is written at two points separated by some small time interval  $\Delta t$ . The time interval is theoretically small enough such that the instantaneous coefficients,  $C_D(t)$  and  $C_M(t)$ , are assumed to remain constant (Ref 12) despite the small but finite variations in

the experimentally measured force record,  $F(t)$ , and the horizontal velocity record,  $U(t)$ . Note that all of the variables in the two equations shown in Figure 7 are known except for the two instantaneous force coefficients  $C_D(t)$  and  $C_M(t)$ . That is,  $F_1(t)$ ,  $F_2(t+\Delta t)$ ,  $U_1(t)$ ,  $U_2(t+\Delta t)$ , the fluid density,  $\rho$ , and the pile diameter,  $D$ , are all known or have been measured experimentally. The horizontal accelerations  $\partial U_1(t)/\partial t$  and  $\partial U_2(t+\Delta t)/\partial t$  have been determined from the numerical derivative of the velocity record by PREPROS as previously described. Consequently having two independent equations allows the solution of the two instantaneous unknown force coefficients,  $C_D(t)$  and  $C_M(t)$ , by COEFFJD using conventional matrix manipulation methods.

A flow chart for COEFFJD is provided in Figure 8. As shown in Figure 8, the program logic is relatively simple and does not require subroutines.

COEFFJD organizes three separate output files. The first of these output files is called COEFF.OUT. This output file is primarily an echo of the input and computed variables. COEFF.OUT was used in the program debugging effort and is retained so that the user can review the input and program calculations. This allows the user to verify that the program is operating correctly and that the input was appropriate.

The second output file is called BADCOEFF. This output file records the data for those cases in which the computed instantaneous drag or inertia coefficients are considered questionable. This occurs when either the water particle velocity or acceleration is very small and the data is ill-conditioned for the solution of the respective coefficient. This can also occur when the drag or inertia force component is a relatively small percentage of the total measured force. In this case, the coefficient computed for this small force component is not relevant. Finally, in some cases COEFFJD computes negative instantaneous force coefficients. Since the coefficients are not vector quantities they may not be signed values. Consequently these coefficients are physically irrelevant. In each of the above cases the data point number at the midpoint of the time interval being analyzed, the computed drag coefficient and inertia coefficient, the average measured force and velocity in the time interval, the ratio of the drag force component to the average measured force in the time interval, the average acceleration in the time interval, the

ratio of the inertia force component to the average measured force in the time interval, and the total number of negative drag coefficients and inertia coefficients are written (in that order) on the BADCOEFF output file. In those cases where a negative coefficient was computed, a warning message is printed along with the data. In the cases where the data was ill-conditioned for the computation of one of the force coefficients, that coefficient is assigned a zero value by COEFFJD. The other coefficient can then be easily computed since it is then the only unknown in the Morison equation (Equation 1). The zero value of the one coefficient and the new computed value of the other coefficient are then written along with the other data items described above on the BADCOEFF file immediately below the original entry. In that way, the user can see what the values of the force coefficients and other pertinent data were before and after one of the coefficients is assigned a value of zero.

The third output file from COEFFJD has a user defined filename that is stored in the variable IOFILE address. This file contains all of the pertinent information to be used as input by the post-processor program in parameterizing and data base managing the force coefficients. Presently the following data are written on the IOFILE variable file:

Line 1:	RUNID	- OSU designated number identifying the experimental run number.
	TARGET	- Target wave period OSU tried to obtain.
	DATAPER	- Actual wave period determined by zero-up-crossing method.
	CUTFREQ	- Cutoff frequency used in filtering the acceleration spectrum. Note: This variable is no longer used since PREPROS has been rewritten to compute the acceleration using only the first two harmonics. It is retained for possible use.
	NWAVE	- The number of the wave being analyzed from this experimental run (usually 1 through 7).

- NPTSPW - The number of digitized data points comprising the wave being analyzed (target = 256 points/wave).
- NFIRST - The data point number corresponding to the first data point of the wave being analyzed.
- NLAST - The data point number corresponding to the last data point of the wave being analyzed.

Line 2: This line of header information is originally left blank since the program must calculate the values of the variables to be written here. At the conclusion of the COEFF analysis of each wave the output file is rewound and the following variables are written in line two of the output header:

- PROCEDURE - The coefficient analysis procedure specified by the user for this analysis - either "END" for end point or "AVE" for the average procedure.
- NTIME - Number of digitized time intervals, dt, used to comprise  $\Delta t$ .
- MCOND - Maximum matrix condition number.
- ZEROU - Effective zero velocity.
- ZEROA - Effective zero acceleration.
- BCM - Number of "bad" or indeterminate inertial coefficients in this wave.
- BCD - Number of "bad" or indeterminate drag coefficients in this wave.

- Line 3: D - Cylinder diameter.
- L - Length of cylinder over which the measured force acts.
- RHO - Fluid density.
- T - Wave period (same as DATAPER in Line 1).
- H - Wave height.

UMAX        - Maximum horizontal water particle velocity.  
VMAX        - Maximum vertical water particle velocity.  
UBAR        - Current velocity in the wave tank.

Line 4: NVTXPER    - The total number of vortex shedding periods in  
                    the entire experimental run being analyzed.

Lines (4+I): NPKTBEG(I) - The data point number corresponding  
                            to the beginning of the I-th vortex  
                            shedding period.

VRTXPER(I) - The I-th vortex shedding period (in  
                            seconds).

NPKTEND(I) - The data point number corresponding to  
                            the end of the I-th vortex shedding  
                            period.

(where: I=1-NVTXPER)

Subsequent to the vortex shedding information, the IOFILE variable output file contains five columns of experimental data that corresponds to the digital time histories for the water surface profile (ft), the horizontal water particle velocity (ft/sec), the horizontal water particle acceleration (ft/sec<sup>2</sup>), the measured in-line force (lb), and the measured transverse force (lb). After that, six columns of data are written on the output file. These data are, respectively, the computed instantaneous drag and inertia coefficients for the time interval being analyzed, the average horizontal water particle velocity during that time interval, the average horizontal acceleration during that time interval, the data point number corresponding to the midpoint of the time interval, and the condition number for the matrix solution of the force coefficients. All of the above data written to the IOFILE variable output file (with the exception of the matrix condition number) are intended for use in parameterizing the force coefficients.

The following COEFFJD program description corresponds to the numbered program steps indicated in Figure 8.

1. **OPEN COEFF.OUT:** COEFFJD opens the COEFF.OUT output file as I/O device six. As described above, this output file receives all of the input data and computed variables during COEFFJD execution. It is useful for debugging and program verification.

2. **OPEN BADCOEFF:** COEFFJD opens the BADCOEFF output file as I/O device seven. As described above, this output file receives pertinent data when either the data is ill conditioned for the solution of one of the force coefficients and it is assigned a zero value, or when a negative force coefficient is computed and the data in the time interval is considered dubious.

3. **INTERACTIVE I/O:** The user specifies the name of the output file from PREPROS to be analyzed by COEFFJD.

4. **READ VORTEX SHEDDING INFORMATION:** The total number of vortex shedding periods in the experimental run is read and stored as NVTXPER. The arrays for the beginning data point number, the period, and the ending data point number for each vortex effecting the transverse force record (NPKTBE(I), VRTXPER(I), and NPKTEND(I), respectively) are filled.

5. **INTERACTIVE I/O:** The user defines the name of the output file that will subsequently be used by the post-processor parameterization program in computing dimensionless parameter values for each of the instantaneous force coefficients. This name is stored in the IOFILE variable address. The user is then prompted to provide the following interactive variables:

MCOND - Maximum matrix condition number used to determine whether the data are well conditioned for the force coefficient solution.

NOTE: This evaluation criteria is no longer used to classify the data as ill-conditioned. However, it may still have value in eliminating ill-conditioned matrices and has been retained for the benefit of future program changes.

- NTIME - Number of digitized time intervals, dt, used to comprise  $\Delta t$  (Figure 9).
- PROCEDURE - Determines whether the "Endpoint" or "Average" coefficient analysis procedure is to be used.
- RZEROF - Decimal fraction of the maximum force in the wave being analyzed that the user wishes to define as zero for computation purposes. The data in the time interval will not be used if the average force in the time interval is too small.
- RZEROU - Decimal fraction of the maximum velocity that the user wishes to define as a zero velocity for computation purposes. For example, if the user specifies 0.1, then COEFFJD will consider all values of the water particle velocity which are less than 10 percent of the maximum velocity in the wave being analyzed to be effectively zero. Hence drag coefficients would not be computed if the average velocity in the time interval being analyzed is below 10 percent of the maximum value.
- RZEROA - Decimal fraction of the maximum acceleration that the user wishes to define as a zero acceleration for computation purposes.
- FORCRT0 - The smallest value of the ratio of the drag or inertia force component to the time interval averaged total measured force that the user still wishes to solve for the respective force coefficient. For example, if the ratio of the drag force component to the total measured force is less than, say, 0.1, the computed drag coefficient might be considered irrelevant by the user. In this case, COEFFJD would solve for the inertial coefficient and assign a zero value to the drag coefficient.
- VISCOS - Fluid kinematic viscosity ( $\text{ft}^2/\text{sec}$ ) for the experimental conditions.

6. **READ INPUT FILE HEADER DATA:** COEFFJD reads the header information on the user specified input file and echoes this data to line 1 and line 3 of the IOFILE variable output file

7. **READ INPUT FILE DATA ARRAYS:** The time history data for the water surface profile (ft), the horizontal water particle velocity (ft/sec), the horizontal water particle acceleration (ft/sec<sup>2</sup>), the in-line force (lb), and the transverse force are read and echoed onto the IOFILE variable output file.

8. **COMPUTE ZEROU, ZEROA, ZEROF:** The user defined effective zero velocity, ZEROU, is computed by multiplying the input variable RZEROU times UMAX. The effective zero acceleration, ZEROA, is approximated by multiplying RZEROA times UMAX times the quantity  $2\pi/T$ . These last two terms are the amplitude of the first term in the Fourier expansion of the acceleration. This approximation is employed because the maximum acceleration is not identified in PREPROS. It provides a reasonable estimate of the maximum acceleration and is well suited for the calculation of the user defined effective zero acceleration. The user defined effective zero force is computed by multiplying the input variable RZEROF times FMAX. As indicated previously, these computational zero values are used by COEFFJD to determine whether the data is ill-conditioned for the computation of one (ZEROU and ZEROA) or both (ZEROF) of the force coefficients.

9. **DEFINE THE INTERVAL ENDPOINT AND AVERAGE VALUES:** COEFFJD allows the user the choice of two procedures to define the time interval endpoint values  $U_1(t)$ ,  $U_2(t+\Delta t)$ ,  $F_1(t)$ , and  $F_2(t+\Delta t)$  (Figure 7) for the computation of the force coefficients. The user may specify either the ENDPOINT or the AVERAGE procedure using the PROCEDURE variable described in paragraph 5, Interactive Input. The ENDPOINT procedure is extremely simple and defines  $U_1(t)$ ,  $F_1(t)$ ,  $U_2(t+\Delta t)$ , and  $F_2(t+\Delta t)$  as those values of the measured velocity and force record on the respective ends of the time step,  $\Delta t$ , as shown in Figure 9a. The AVERAGE procedure defines the values  $U_1(t)$ ,  $U_2(t+\Delta t)$ ,  $F_1(t)$ , and  $F_2(t+\Delta t)$  as the average of the measured velocity



and force values during the first and second halves, respectively, of the time step  $\Delta t$ . This process is illustrated in Figure 9b for a case in which "NTIME" (see paragraph 5, Interactive Input) equals four digitized time intervals ( $dt$ ) (i.e.,  $\Delta t = 4 \times dt$ ). The AVERAGE procedure is recommended over the ENDPOINT procedure when the user wishes to employ a large time step  $\Delta t$ .

The accelerations,  $A_1 = \partial U_1(t)/\partial t$  and  $A_2 = \partial U_2(t+\Delta t)/\partial t$ , necessary for the inertial force term in the Morison equation (see Figure 7) are defined in the same manner as  $U_1(t)$ ,  $U_2(t+\Delta t)$ ,  $F_1(t)$  and  $F_2(t+\Delta t)$  depending on whether the ENDPOINT or AVERAGE procedure is chosen. However, instead of using measured data, COEFFJD employs the acceleration time history computed by PREPROS as the filtered numerical derivative of the velocity record. As noted previously, these are the only variables that could not be measured experimentally and the veracity of the computed values  $A_1$  and  $A_2$  is difficult to verify.

It is useful to know interval averaged values of the velocity, force, and acceleration data (UBAR, FBAR, and ABAR) for parameterization purposes. When the ENDPOINT procedure is chosen, these interval averages are defined as the sum of the endpoint values divided by two, (e.g., the interval averaged velocity, UBAR, is obtained as  $(U_1 + U_2)/2$ ). An identical process is also used when the AVERAGE procedure is employed. That is, the average velocity during the time step is again obtained as  $(U_1 + U_2)/2$ . Note, however, that this is not rigorously correct for cases where NTIME is even as in the case shown in Figure 9b. This occurs because the middle velocity ( $U(C)$  in Figure 9b) is counted twice. An algorithm is flagged when NTIME is even to correct the computation of the average values during the time step.

**10. DEFINE UMID, AMID, AND FMID:** In some cases it may be more appropriate to use the value of the velocity, acceleration, or the force data at the midpoint of the time interval as opposed to the interval averaged values (UBAR, ABAR, and FBAR defined above). COEFFJD defines UMID, AMID, and FMID as the midpoint datum in the time interval when NTIME is an even number (e.g.,  $UMID = U(C)$  in Figure 9). When NTIME is odd, the midpoint values are defined as the average of the two data values on either side of the middle of the time interval.

11. **IF FBAR .LE. ZEROF:** If the average force in the time interval, FBAR, is smaller than the user defined effective zero force, ZEROF, the measured force data is not considered accurate enough for the computation of the force coefficients. COEFFJD discards this data and proceeds to the next time interval.

12. **COMPUTE MATRIX CONDITION NO. AND DETERMINANT:** Since the instantaneous Morison equation force coefficients being sought are the solutions to a system of two simultaneous equations, standard matrix manipulation procedure may be employed. The condition number of a matrix is a measure of the sensitivity of a matrix equation solution ( $C_D, C_M$ ) to errors in the data (measured forces) or errors in the matrix elements (measured kinematics). The condition number of a matrix is defined as the norm of the matrix times the norm of its inverse. A large matrix condition number is indicative of the fact that the data are ill-conditioned for the solution of the force coefficients. Although COEFFJD no longer utilizes the matrix condition number to suspend one or both of the force coefficient computations, the matrix condition number is recorded on the IOFILE variable output file with each of the instantaneous force coefficients. The user may wish to use this value as an indicator or for some form of parameterization value.

A large matrix condition number is usually a consequence of a vanishing determinant. Since the matrix determinant is proportional to  $U_1 A_2 - U_2 A_1$ , it will approach zero as either both the velocities or both the accelerations tend toward zero. Although such an occurrence indicates the data are ill-conditioned for finding both of the force coefficients, they still may be well conditioned for finding one of the coefficients. That is, as the velocities vanish for example and the determinant goes to zero, the data may still be well conditioned for solving for the inertial coefficient,  $C_M$ . Hence, in the succeeding steps, the value of the matrix determinant is checked to see if the solution for only one of the force coefficients is appropriate.

13. IF DET .EQ. 0.0...: COEFFJD checks to see if the determinant is zero. If it is and the accelerations A1 and A2 are both less than the defined effective zero acceleration, ZEROA, then a solution for only the instantaneous drag coefficient is sought. Similarly, if the determinant is zero and the velocities U1 and U2 are both less than the defined effective zero velocity, then a solution for only the instantaneous inertia coefficient is sought. If the determinant is zero and neither of the above conditions for A1, A2, U1, and U2 are true, COEFFJD proceeds on to the next time interval.

14. SOLVE FOR  $C_D(t)$ ,  $C_M(t)$ : The matrix equation:

$$\begin{bmatrix} C_D \\ C_M \end{bmatrix} = [B]^{-1} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}$$

where:

$$[B] = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \rho D L U_1 |U_1| & \frac{1}{4} \rho L \pi D^2 A_1 \\ \frac{1}{2} \rho D L U_2 |U_2| & \frac{1}{4} \rho L \pi D^2 A_2 \end{bmatrix}$$

$$[B]^{-1} = \frac{\begin{bmatrix} b_{22} & -b_{12} \\ -b_{21} & b_{11} \end{bmatrix}}{(b_{11} b_{22} - b_{12} b_{21})}$$

is solved to yield the instantaneous force coefficients as:

$$C_D(t) = \frac{(b_{22} F_1 - b_{12} F_2)}{(b_{11} b_{22} - b_{12} b_{21})}$$

$$C_M(t) = \frac{(-b_{21} F_1 + b_{11} F_2)}{(b_{11} b_{22} - b_{12} b_{21})}$$

15. COMPUTE FDRAG, FINERTA, RTODRAG, RTONRTA: The Morison equation drag and inertia force components are computed as:

$$FDRAG = C_D(t) \frac{\rho}{2} D L UBAR |UBAR|$$

$$FINERTA = C_M(t) \frac{\rho}{4} L \pi D^2 ABAR$$

The ratio of the drag force, RTODRAG, and inertia force, RTONRTA, components to the interval averaged force, FBAR, are computed as:

$$RTODRAG = |FDRAG/FBAR|$$

$$RTONRTA = |FINERTA/FBAR|$$

16a. IF RTODRAG .LT. FORCRT0 .OR. |UBAR| .LT. ZEROU: If the computed drag force component represents only a small fraction of the total force (i.e., the ratio of the drag component to the interval averaged force is less than the user defined force ratio, FORCRT0), or if the interval averaged water particle velocity is less than the defined effective zero velocity, then the drag coefficient obtained in step 15 is meaningless. In this case, COEFFJD will recompute the inertia coefficient and assign a zero value to the drag coefficient (see Step 17 below). Pertinent data for this time interval will be written to the output file BADCOEF.

16b. IF RTONRTA .LE. FORCRT0 .OR. |ABAR| .LT. ZEROA: Analogous to Step 16a, COEFFJD will recompute the drag coefficient (see Step 18) when the inertial force component contributes negligibly to the interval averaged force or if the interval averaged acceleration is less than the defined effective zero water particle acceleration.

17. SOLVE FOR  $C_M(t)$  ONLY: COEFFJD assigns a value of zero to the drag coefficient and solves for  $C_M(t)$  as:

$$C_M(t) = \frac{F}{\left(\frac{\rho}{4} L \pi D^2 A\right)}$$

The values used for F and A are FMID and AMID unless AMID equals zero. In that case F1 and A1 are used unless A1 equals zero also. In that case F2 and A2 are employed. As previously indicated, the original drag coefficient computed in Step 15 is designated as a "bad coefficient".

The pertinent data for the original force coefficient calculation and the recomputation of  $C_M$  are written to the BADCOEFF output file (see Step 20).

18. **SOLVE FOR  $C_D(t)$  ONLY:** COEFFJD assigns a value of zero to the inertia coefficient and solves for  $C_D(t)$  as:

$$C_D(t) = \frac{F}{\left(\frac{\rho}{4} L D U |U|\right)}$$

The values for F and U are FMID, UMID, or F1, U1, or F2, U2 as described above. The data are recorded on the BADCOEF output file as indicated in Step 20.

19. **IF  $C_D(t)$  .OR.  $C_M(t) = 0.0$ :** COEFFJD checks to see if a bad coefficient has been replaced with a zero. If it has then the data must be written to the BADCOEFF output file.

20. **WRITE:** The following variables are written on the BADCOEFF output file both before and after the recomputation of the single force coefficient solution:

TIME	- The data point number at the middle, beginning, or end of the interval (depending on whether FMID, F1, or F2 is used).
CD	- The instantaneous drag coefficient for the interval.
CM	- The instantaneous inertia coefficient for the interval.
FBAR	- Interval averaged in-line force.
UBAR	- Interval averaged horizontal water particle velocity.
RTODRAG	- Ratio of the drag force component to FBAR.
ABAR	- Interval averaged horizontal water particle acceleration.
RTONRTA	- Ratio of the inertia force component to FBAR.
X1	- $b_{11}$ value of the B matrix (see Step 14).
Y1	- $b_{12}$ value of the B matrix.
X2	- $b_{21}$ value of the B matrix.
Y2	- $b_{22}$ value of the B matrix.

21. IF  $C_D(t)$  .OR.  $C_M(t)$  .LT. 0.0: COEFFJD checks to see if a negative coefficient value has been computed. As stated previously, the Morison equation force coefficients are not vector quantities. Hence, a negative value renders them physically meaningless. If one of the coefficients is negative, the pertinent data will be recorded on the BADCOEFF output file with a warning message (see Step 22). The data and coefficients from this interval will be discarded.

22. WRITE: If a negative coefficient value is detected, the pertinent data and a warning message are recorded on the BADCOEFF output file. The same variables described in Step 20 are recorded with the exception of the B matrix values. Instead, the cumulative number of negative drag coefficients and negative inertia coefficients encountered so far in the wave being analyzed are output.

23. WRITE: Having sorted out and discarded the ill-conditioned data and resulting coefficients, COEFFJD records the remaining instantaneous drag and inertia coefficients, the interval averaged horizontal water particle velocity and acceleration values, the mid-interval data point number, and the matrix condition number. These values are written on the IOFILE variable output file for parameterization and data base managing by the post-processor program.

24. IF NEXT AT: If another time interval exists in the wave being analyzed, COEFFJD will loop back to Step 9 and begin the definition of the endpoint values for the next time interval. If there are no more time intervals in the wave being analyzed, the program will proceed to Step 25.

25. NEXT WAVE?: COEFFJD asks the user if it should begin processing the data from the next wave in the specified input file. If there are no more waves to be analyzed, COEFFJD prompts the user to end the program.

## COEFFJD SUMMARY

COEFFJD is the processor computer program that computes the instantaneous drag and inertia coefficients for use in the Morison equation in the time domain. COEFFJD accomplishes this by analyzing the input data file organized by the preprocessor program, PREPROS, and solving a system of two simultaneous equations using conventional matrix manipulation methods. The two simultaneous equations are obtained by writing the conventional Morison equation, Equation 1, at two times separated by a small time interval,  $\Delta t$ . COEFFJD allows the user two options for defining the necessary endpoint values of force, water particle velocity, and acceleration on either end of the time interval. The program also attempts to filter out ill-conditioned data and write it to a specific output file for user review. COEFFJD organizes an output file of instantaneous force coefficients and variables necessary for post-processing to parameterize and data base manage the coefficients.

## TASK 3

As stated previously, this task required the development of dimensionless parameters for the parameterization of the instantaneous force coefficient data sets developed in Task 2. These parameterized data sets then require a data base management system to allow the user to retrieve the necessary instantaneous force coefficients given the appropriate fluid, flow field, and structural variables comprising the dimensionless parameters.

The former portion of this task has been completed; that is, a set of dimensionless parameters has been developed. The completeness of this dimensionless parameter set is open to conjecture; however, several attempts have been made to include as many combinations as possible of variables which could be hydrodynamically significant. The set of dimensionless parameters is organized into a primary set and a secondary set. The former set should be tried as a first attempt at the parameterization process with parameters deleted (or added from the secondary set) as the

need arises. It should be noted that the primary set is significantly expanded over and above the conventional Morison equation force coefficient parameters of Reynolds number and Keulegan-Carpenter number and that both wave-period-invariant and instantaneous parameters are included. The following brief description is provided to summarize the primary and secondary dimensionless parameters developed in this task.

### Primary Parameters

#### 1. Flow Regime (4 types):

Regime I:  $U(t) = \text{positive value}, A(t) = \text{negative value}$

Regime II:  $U(t) = \text{negative value}, A(t) = \text{negative value}$

Regime III:  $U(t) = \text{negative value}, A(t) = \text{positive value}$

Regime IV:  $U(t) = \text{negative value}, A(t) = \text{positive value}$

where:  $U(t) = \text{appropriate interval average velocity}$   
(e.g.,  $UBAR, UMID$ )

$A(t) = \text{appropriate interval average acceleration}$   
(e.g.,  $ABAR, AMID$ )

This parameter provides information as to what the flow field is doing during the time interval (i.e., (I) positive decelerating flow, (II) negative decelerating flow, etc.).

#### 2. Reynolds Number (two types):

$$\text{Constant: } \frac{|U|_{\max} D}{\nu}$$

$$\text{Instantaneous: } \frac{U(t) D}{\nu}$$



where:  $|U|_{\max}$  = the maximum absolute value of the horizontal water particle velocity during the wave being analyzed

$D$  = cylinder diameter

$\nu$  = fluid kinematic viscosity

This parameter is the ratio of the inertial to viscous forces and provides an indicator of the turbulent intensity of the flow field.

3. Keulegan-Carpenter Number (constant only):

$$\frac{|U|_{\max} T}{D}$$

where:  $T$  = period of the wave being analyzed

This parameter provides information regarding drag or inertial force predominance and the onset of flow separation and wake effects.

4. Relative Current Strength (two types):

Constant:  $\frac{V_c}{|U|_{\max}}$

Instantaneous:  $\frac{V_c}{U(t)}$

where:  $V_c$  = return current magnitude (i.e., the wave period average of the water particle velocity time history)

This parameter provides a measure of how a current in the flow effects the flow field by advection of vortices and wake disruption.

5. **Orbital Eccentricity (constant only):**

$$\frac{|W|_{\max}}{|U|_{\max}}$$

where:  $|W|_{\max}$  = the maximum absolute value of the vertical water particle velocity during the wave being analyzed.

This parameter describes whether the water particle orbits are circular (deep water waves), elliptical, or nearly flat (shallow water waves) and provides information regarding vortex advection and wake generation.

6. **Relative Force Strength (nine types):**

Constant:  $F_{I_{\max}}/F_{\max}$

$$F_{D_{\max}}/F_{\max}$$

$$F_{I_{\max}}/F_{D_{\max}}$$

Instantaneous:  $F(t)/F_{\max}$

$$F_I(t)/F_{\max}$$

$$F_D(t)/F_{\max}$$

$$F_I(t)/F(t)$$

$$F_D(t)/F(t)$$

$$F_I(t)/F_D(t)$$

where:  $F_{\max}$  = largest force value measured during the wave period being analyzed

$F_{I_{\max}}$  = largest inertial force component during the wave period

$F_{D_{\max}}$  = largest drag force component during the wave period

$F(t)$  = interval averaged in-line force (e.g., FBAR, FMID)

$F_I(t)$  = interval averaged inertia force component

$F_D(t)$  = interval averaged drag force component

Similar to the Keulegan-Carpenter number, these parameters provide information regarding the relative importance of the drag and inertial forces. These nine parameters are not all required. They are presented for future researchers to evaluate and choose the most pertinent.

#### 7. Vortex Shedding Frequency (two types):

Constant:  $\frac{T}{(T_{vs})_{\text{avg}}}$

Instantaneous:  $\frac{T}{T_{vs}}$

where:  $(T_{vs})_{\text{avg}} = \frac{\sum_{i=1}^{N_{vs}} T_{vs}(i)}{N_{vs}} = \text{average vortex shedding period during the wave cycle being analyzed}$

$N_{vs}$  = number of vortices shed during the wave cycle

$T_{vs}$  = vortex shedding period which spans the time interval being analyzed

These parameters provide a measure of the relative importance of the vortex shedding frequency.

8. Froude Number (constant only):

$$\frac{|U|_{\max}}{\sqrt{g D}}$$

where:  $g$  = gravitational acceleration

This parameter provides a measure of the ratio of the inertial forces to gravitational forces.

9. Frequency Parameter (constant only):

$$\frac{D^2}{\nu T}$$

This parameter is the ratio of the Reynolds number to the Keulegan-Carpenter number. Since both of these parameters are already included this parameter is probably redundant. It is provided here for the purposes of user evaluations.

10. Strouhal Number (4 types):

$$\text{Constant: } \frac{D}{|U|_{\max} \bar{T}_{vs}}$$

$$\text{Semi-instantaneous: } \frac{D}{|U|_{\max} T_{vs}}$$

$$\frac{D}{U_{\max} T_{vs}}$$

$$\text{Instantaneous: } \frac{D}{U(t) T_{vs}}$$

where:  $\bar{T}_{vs}$  = average vortex shedding period during an entire run with multiple monochromatic waves

$U_{max}$  = largest value (negative or positive sign retained) of the horizontal water particle velocity during the wave cycle being analyzed

These parameters also give a measure of the importance of the vortex shedding frequency. They may be redundant to the Vortex Shedding Frequency parameter (see Parameter 7) and it is unlikely that all four types would be required in any case.

#### Secondary Parameters

The following parameters generally are conventional wave field parameters or are ratios of other dimensionless parameters. Their significance to the present hydrodynamic interaction problem is unknown, or in some cases, they are redundant to the primary parameters. They are proposed for future researchers to evaluate in the event that the primary dimensionless parameter list does not provide comprehensive parameterization.

##### 11. Constant:

$$\frac{D}{g T^2}$$

This parameter is the ratio of the Froude number squared over the Keulegan-Carpenter number squared.

##### 12. Ursell Parameter (Constant only):

$$\frac{L^2 H}{d^3}$$

where:  $L$  = the wavelength

$H$  = the wave height

$d$  = the water depth

13. **Modified Ursell Parameter (constant only):**

$$\frac{L H^2}{d^3}$$

Note that wave height squared provides a measured of the incident wave energy.

14. **Wave Phase (instantaneous only):**

$$\frac{t}{T}$$

where:  $t$  = the elapsed time in the wave cycle

15. **SPM (constant only):**

$$\frac{H}{g T^2}$$

16. **Constant:**

$$\frac{|U|_{\max}^2}{g D^2}$$

This parameter is the ratio of the Froude number squared to the Reynolds number and expresses the ratio of viscous forces to gravitational forces.

17. Constant:

$$\frac{|U|_{\max}}{g T}$$

This parameter is the ratio of the Froude number squared to the Keulegan-Carpenter number.

18. Relative Roughness (constant only):

$$\frac{\varepsilon}{D}$$

where:  $\varepsilon$  = height of surface irregularities on the cylinder  
or pile

This parameter is useful for those cases in which a roughened surface effects the boundary layer and the separation and wake formation characteristics of the flow.

The second portion of Task 3, the development of the post-processor program to compute the values of the dimensionless parameters for each instantaneous force coefficient, has not been completed. An initial programming effort which employed only the Reynolds number and Keulegan-Carpenter number had been completed but was inadequate for the parameterization of the instantaneous coefficients. This effort remains a topic for future research. However, before this effort is undertaken, the more important questions of how and why negative force coefficients are being generated from ostensibly well conditioned data must be answered. As will be discussed in the Results section of this report, these two questions and the questions associated with the generation of the horizontal water particle acceleration time history as the numerical derivative of the velocity consumed a large portion of this research effort.

## RESULTS

Instantaneous wave force coefficients have been generated for nearly all of the monochromatic OSU experimental wave data. However, none of these coefficients have been archived for parameterization and data base management. This is due to the unexplained generation of negative drag coefficients from ostensibly well conditioned data in some of the data analysis. Figure 10 provides a representative example of this problem. It may be expected that the drag coefficient computation would tend to be prone to error in those regions where the water particle velocity approaches zero. Note, however, that negative drag coefficients occur over unacceptably large values of time (wave phase) in which the velocity values are not necessarily approaching zero. For example, consider the 4.6-second period, 4.3-foot-high wave case shown in Figure 11. It is apparent from the large shaded area from approximately  $20^{\circ}$  to  $130^{\circ}$  wave phase that the negative drag coefficients occurred in the regions around the maximum water particle velocity. This is unacceptable since the drag coefficient is not a vector quantity and hence may not be a signed value. That is, if the drag coefficient was allowed to have a negative value, it would indicate that the direction of the applied drag force would oppose the flow direction.

Hence, the computation of negative drag coefficients is a serious problem which demands investigation prior to the generation, archiving, and parameterization of instantaneous force coefficient data sets. Some insight into why the negative drag coefficients occurred for the 4.6-second period, 4.3-foot-high wave case of Figure 11 can be obtained by plotting the measured in-line force, velocity, and numerically derived acceleration time histories as shown in Figure 12. It can be seen in Figure 12 that the measured force is very nearly in phase with the acceleration for about the first half of the wave. This implies that the inertial force component is the only significant contributor to the measured force plotted in Figure 12. As would be expected for this condition with significant measured velocities, the computed drag coefficients are nearly zero albeit slightly negative.



The question as to why the drag force component does not contribute to the measured force is difficult to answer. For a free stream flow case with a velocity of approximately 2.8 ft/sec (see Figure 12 at a wave phase value of approximately  $86^{\circ}$ ) the drag force would equal about 9 pounds. However, for this wave flow Figure 12 shows that the measured force (and the acceleration) is zero when the velocity is about 2.8 ft/sec. This research has not developed an answer for this anomalous behavior. However, there are four known possibilities that could explain it. The first two possibilities deal with inaccuracies in the measured or computed force, velocity, or acceleration time histories. The second two possibilities concern the inability of the force/kinematics models to replicate the physics of the dynamic pressure and flow fields in the near vicinity of the test pile. These four possibilities are summarized below:

1. Measurement Phase Shift: As indicated, both the wave-induced hydrodynamic force and horizontal water particle velocity were measured directly during the OSU experiments. The data acquisition techniques used to measure, transmit, filter, digitize, and record this data electronically are fully documented in Reference 14. It is known that some of these electronic processes produce phase shifts in the data records. Considerable effort was expended in the OSU experiments to properly account for these phase shifts. However, due to the complexity of wave force experiments, there is always a significant multiplication factor for Murphy's Law despite the best experimental efforts. It is easy to demonstrate that a phase shift of the measured velocity relative to the measured force would produce drastic effects in the drag and inertia force relative contributions to the total force. This would cause significant variation in the computed instantaneous force coefficients. For example, if a negative 20-degree phase shift had occurred in the velocity record relative to the force record for the wave measurements shown in Figure 12, then correcting that phase shift would yield Figure 13. Note in Figure 13 that the acceleration history has also been shifted with the velocity since the relative phases between these two records should be preserved. Examination of Figure 13 reveals that both the velocity

(drag force) and acceleration (inertial force) would be contributing appropriately to the measured force. This does not verify that phase shifting of the experimental variables actually occurred in the OSU data. It does, however, indicate that this is one possible explanation for some of the problems. Since measurement phase shifts are always an experimental consideration, it is strongly recommended that future wave force experiments employ an electronic phase pulse system. This system would introduce a 5-volt pulse signal simultaneously at each measurement device on a periodic basis. This would allow temporal comparisons of these data spikes in the various measurement records to exactly determine the electronic phase shifting. The spike distortion in the measurement record could subsequently be corrected using interpolating techniques.

2. Inaccurate Numerical Acceleration: Nath (Ref 15 and 16) has demonstrated that the OSU experimental wave force data set is inertially dominated. Hence, it is critical to the evaluation of accurate instantaneous force coefficients that an accurate numerical acceleration be computed. Since the numerical acceleration is computed as the numerical derivative of the velocity record, it is imperative that both the measured velocity record and the numerical derivative procedure be accurate in magnitude and phase information. Possible problems in producing an accurate velocity record due to phase shifting were discussed above. It was noted that an erroneous phase shift in the velocity record would cause a similar shift in the computed acceleration. It is also possible that the numerical derivative process produces an inaccurate acceleration record. Considerable effort has been expended to verify that the FFT algorithm employed in computing the numerical acceleration does not introduce a numerical phase shift in the acceleration relative to the velocity. The exercises conducted to achieve Table 1 have demonstrated that it is possible to transform the velocity record back and forth between the time domain and the frequency domain without any numerical shifting. Since only angular frequency multiplication, sign changes, and FFT coefficient inversion are necessary to compute the acceleration spectrum, it is unlikely that a numerical phase shift is occurring in the acceleration

time history computation; however, the description of the ACCEL subroutine in the preprocessor program PREPROS has noted that the numerical derivative process does accentuate extraneous noise. The problems associated with filtering this noise are described in that documentation. It is sufficient to note here that this filtration process may produce local inaccuracies in the acceleration time history. Since the OSU data are inertially dominated, these local inaccuracies in the acceleration record would result in inaccurate instantaneous coefficients. This possible problem is compounded by the fact that the theoretical maximum accelerations occur as the velocity approaches zero. That is, the largest and possibly most important accelerations are being derived from the velocity data that are the most questionable.

3. Improper Force Modeling: The Morison equation may not be able to model the physics of the wave-structure hydrodynamic interaction process on a small subperiodic time scale or at a small localized vicinity about the structure. This could occur because the Morison equation implies a Froude-Krylov hypothesis that the presence of the structural member has no significant effect on the wave field. Hence the Morison equation models the force as the wave pressure gradient force that would have been accelerating the water particles if the structure wasn't there with only two specific corrections to account for the additional energy extracted from the flow field due to added mass effects and the high-low pressure zones created by flow stagnation and separation effects. There is no guarantee, however, that these corrections are capable of modeling the highly localized subperiodic temporal variations in the pressure and flow field about the structure during the wave cycle. It is asking a lot from the Morison equation to model these complex hydrodynamic phenomena in the aggregate, or average, sense over a wave cycle much less the subperiodic characteristics as well. Obviously using a force model which was inappropriate on a subperiodic basis to yield subperiodic coefficients would produce incorrect results.

4. Improper Flow Modeling: The kinematics values used in the Morison equation are the velocity and accelerations of the water particles under a wave without the influence of a structure. In the OSU experiment the water particle velocities were measured adjacent to the test pile but offset by a few feet. This measurement technique quantifies the wave induced hydrodynamic fluid velocities but yields no information regarding the local and temporal fluid velocity effects in the near vicinity of the cylinder. That is, the measured velocity record may be considerably different than the fluid velocity history that the test pile actually saw. This difference is due to the fact that the flow field about the cylinder is constantly being adjusted due to vortex generation, shedding, decay, and reimpingement on the cylinder as the water particles change direction. Hence, the local fluid velocities about the test pile differ appreciably from the measured values employed by the Morison equation. It was hoped that instantaneous force coefficients could account for this difference but it is possible that this is inappropriate and, therefore, the instantaneous force coefficients are erroneous.

It is not known decisively which of the above four error possibilities explain the discrepancies encountered during this research effort. They may all be contributing factors. The final answers remain a topic for future research efforts.

#### SUMMARY

Navy utilization of fixed and floating space-frame ocean structures has increased during recent years. These facilities must withstand ocean environmental loadings due to waves, wind, ice, earthquakes, etc. In order to design these structures to withstand the various imposed environmental loads, Navy design engineers must first have a means to quantify the magnitudes of the design loads. For structures that respond dynamically, the design engineers must be able to specify the temporal fluctuations of the load as well as the magnitudes. That is, in order to calculate the dynamic structural response, they must be able to predict the

applied force history for a given set of environmental conditions. The intent of this research effort was to enhance the design engineer's capability to predict wave-induced hydrodynamic loads for given wave conditions.

For structural members whose cross-sectional dimensions are small relative to the incident wave length, applied wave loads are computed using the Morison equation. This equation is a semi-empirical model in which the wave force is evaluated per unit length of the structural member as the sum of a drag force term and an inertial force term. The Morison equation temporal dependence is provided by the theoretical water particle velocity and acceleration (kinematics) terms. There are no other terms in the Morison equation that are functions of time. That is, there are no other terms that are functions of the wave phase and the time-varying flow field. Furthermore, the theoretical kinematics provide no information regarding the subperiodic fluctuations in the flow and pressure fields in the near vicinity of the structural members due to vortex shedding or other unsteady hydrodynamic phenomena. This information could be provided by the force coefficients,  $C_D$  and  $C_M$ ; however, general practice renders these coefficients temporally invariant by averaging regression analysis techniques, such as least square or Fourier analysis techniques. This research hypothesized that these averaging schemes are inappropriate and that this partially accounts for the discrepancy between measured and predicted force histories.

This research proposed that a set of instantaneous force coefficients be developed that account for the subperiodic temporal fluctuations in the flow and pressure fields. These coefficients must be parameterized using the fluid, flow field, and structural variables readily available to the designer. To this end, this research established three tasks to be completed:

1. Locate an acceptable wave force experiment that satisfied the criteria of high quality wave kinematics and force measurements. The data from the experiment must be database managed into an acceptable format for time domain solution of instantaneous wave force coefficients.

2. Develop a high speed numerical algorithm that will process the experimental data in the time domain to yield instantaneous drag and inertia coefficients for the Morison equation.

3. Develop appropriate dimensionless parameters and post-process the force coefficients into a matrix configuration data base. The data base must be appropriately parameterized so that the designer can retrieve the necessary instantaneous force coefficients given the appropriate fluid, flow field, and structural variables comprising the dimensionless parameters.

Task 1 was completed using the Oregon State University wave force experimental data for a 12-inch vertical cylinder and the preprocessor computer program PREPROS. This program performs the following useful functions necessary for the subsequent determination of the instantaneous force coefficients:

1. Reads and organizes the raw experimental data.
2. Subdivides the continuous data record into individual wave increments.
3. Determines the maximum horizontal and vertical water particle velocities, the wave height, and the average return current for each wave.
4. Computes the horizontal water particle acceleration from the measured velocity.
5. Performs the forward and inverse fast Fourier transforms of any user-specified data recorded.
6. Numerically filters any specified data record.

7. Analyzes the transverse force record to determine the time interval between dynamic pressure fluctuations due to vortex shedding and wake interaction.

8. Creates a data file for analysis by the force coefficient processor program.

Task 2 was completed via the computer program COEFFJD. This program analyzes the preprocessed experimental wave force data files to compute instantaneous drag and inertia coefficients. This is accomplished by employing the Morison equation at two points (within the wave force and velocity records) that are separated by a small time interval,  $\Delta t$ . Since the wave force and water particle velocities were measured at the two points, and since the water particle acceleration can be computed to first-order accuracy at both points, all of the Morison equation variables are known except for the drag and inertia coefficients. If it is assumed that these force coefficients remain constant over the time interval  $\Delta t$ , and if the time interval is chosen so that finite and nontrivial changes occur in the measured forces and velocities, then a system of two equations and two unknowns is achieved. This is easily solved to obtain the instantaneous drag and inertia coefficients for the particular time interval being analyzed. Instantaneous drag and inertia coefficients are obtained for the entire wave record being analyzed by repeating the process for successive time intervals.

The program allows the user to specify either an "Endpoint" or "Average" procedure to evaluate the forces, velocities, and acceleration corresponding to the two points in the time interval. The instantaneous drag and inertia coefficients are written onto an output file with other fluid, flow field, and structural variables suitable for a post-processor parameterization of the coefficients solved for each time interval in the wave record.

To date, an interesting problem with the computation of some instantaneous negative drag coefficients has been encountered. Since the force coefficients are scalar quantities, negative coefficient values are not physically relevant. In fact, negative coefficient values erroneously

reverse the direction of the applied hydrodynamic force component from the appropriate direction indicated by the sign of the instantaneous fluid velocity or acceleration vectors. Consequently, solutions that yield negative force coefficients are incorrect and invalid.

Efforts to understand the generation of negative drag coefficients have produced four distinct possibilities: First, the fluid acceleration values used in the computation of the force coefficients are computed numerically from the measured fluid velocity record. A phase shift in the numerical acceleration relative to the measured velocity and force records could produce erroneous coefficient values. Also, the numerical differentiation process enhances noise in the measured records - particularly at the higher harmonics. If this noise is not filtered it will result in an erroneous numerical acceleration record and erroneous coefficient values. Second, the phase shifts in the electronic data recording process for the measured velocity and wave force records may not have been properly accounted for in compiling and scaling the data signals into engineering unit time histories. Again, erroneous phase shifts between the fluid velocity, fluid acceleration, and force records would produce erroneous coefficient values. Third, the Morison equation wave force model being used in this investigation may not model the physics of the wave force process on a small subperiodic time scale at a small macro-scale specific location. This could occur because the Morison equation implies a Froude-Krylov large macro-scale hypothesis that the presence of the structural member has no significant effect on the wave field. However, on a small macro-scale in the local vicinity of the test cylinder, there are significant effects on the local velocity and pressure field in both the spatial and temporal sense. This is due to vortex generation and wake effects as the fluid interacts with the test cylinder. Obviously, using an inappropriate force model would lead to incorrect results. Fourth, the fluid velocities used in the computation of the drag coefficient are obtained by measuring the wave water particle orbital velocities adjacent to, but offset by a few feet from, the test cylinder. This measurement technique quantifies the **wave-induced** hydrodynamic fluid velocities but yields no information regarding the **local**



fluid velocity effects in the near vicinity of the cylinder. These local fluid effects that the cylinder "sees" are due to vortex generation, convection, decay, and reimpingement upon the cylinder. Hence, the local fluid velocities on an instantaneous basis may be considerably different than the measured wave-induced fluid velocities at a finite distance away from the cylinders.

Further investigation of the previously described four possibilities has indicated that the negative drag coefficient problem occurs in data records where the numerical acceleration is very nearly in phase with the measured force record. This means that the inertial force component is the only contributor to the total measured force, or conversely, that the drag force component is not contributing to the total measured force despite significant measured velocity magnitudes. Although this finding is interesting, it does not further illuminate which of the above four possibilities is responsible for the negative drag coefficient problem.

The computer program COEFFJD has been rewritten to exclude all data from which negative coefficient values are computed. However, this data is archived so that future investigators encountering similar phenomena can extract and analyze it.

Task 3, the parameterization of the existing instantaneous force coefficients and post-processing into a matrix configuration data base for designer access, has been partially addressed. The current practice of parameterizing the coefficients by the Reynolds number and Keulegan-Carpenter number is inadequate and has been expanded to include a number of other periodic and subperiodic parameters. The development of the post-processor computer programs to compute the values of the dimensionless parameters for each pair of instantaneous force coefficients and data base manage the coefficient set has not been accomplished. This is due to the inability to decisively explain the generation of negative force coefficients.

## CONCLUSIONS

This research did not reach definitive conclusions regarding instantaneous wave force coefficients due to the generation of some invalid negative drag coefficients as described above. It is therefore concluded that:

- (1) The validity of instantaneous Morison equation wave force coefficients is still unknown.
- (2) This effort should be repeated with another wave force data set to see if negative force coefficients are generated again.
- (3) Future laboratory or ocean wave force experiments must be conducted with an instrumentation system that demonstrates that all electronically recorded data records are phase locked.

## FUTURE RESEARCH

This research did not reach definitive conclusions. It is recommended that this effort be tried again with another wave force data base. This data base should possess the accuracy and scale of the OSU experiments. However, the phase relationship between the measured force, water particle velocity, water surface profile, and local pressure field must be verified by a simultaneous digital pulse signal introduced at each measurement device. In addition, accurate nonintrusive means of measuring the water particle velocities both far away from and in near proximity to the test pile should be employed. Laser-Doppler velocimeter techniques may be useful for this.

If the problem with the generation of negative coefficients can be cleared up it is recommended that this research be extended to an ocean data set. This additional research is considered necessary because the confused three-dimensional flow fields found in the ocean may tend to mitigate the importance of the temporal fluctuations due to, for example, vortex shedding and wake encounter. That is, the increased turbulence

and randomness of the ocean environment may provide a natural averaging process such that the use of period averaged force coefficients (vice instantaneous coefficients) may be appropriate. However, if it turns out that instantaneous coefficients are required for ocean design conditions, research efforts should continue on the generation of a comprehensive fully parameterized instantaneous coefficient set. The parametric data set could then be analyzed using regression analysis techniques to try and generate analytical descriptions for the drag and inertia coefficients in some simplified tractable format.

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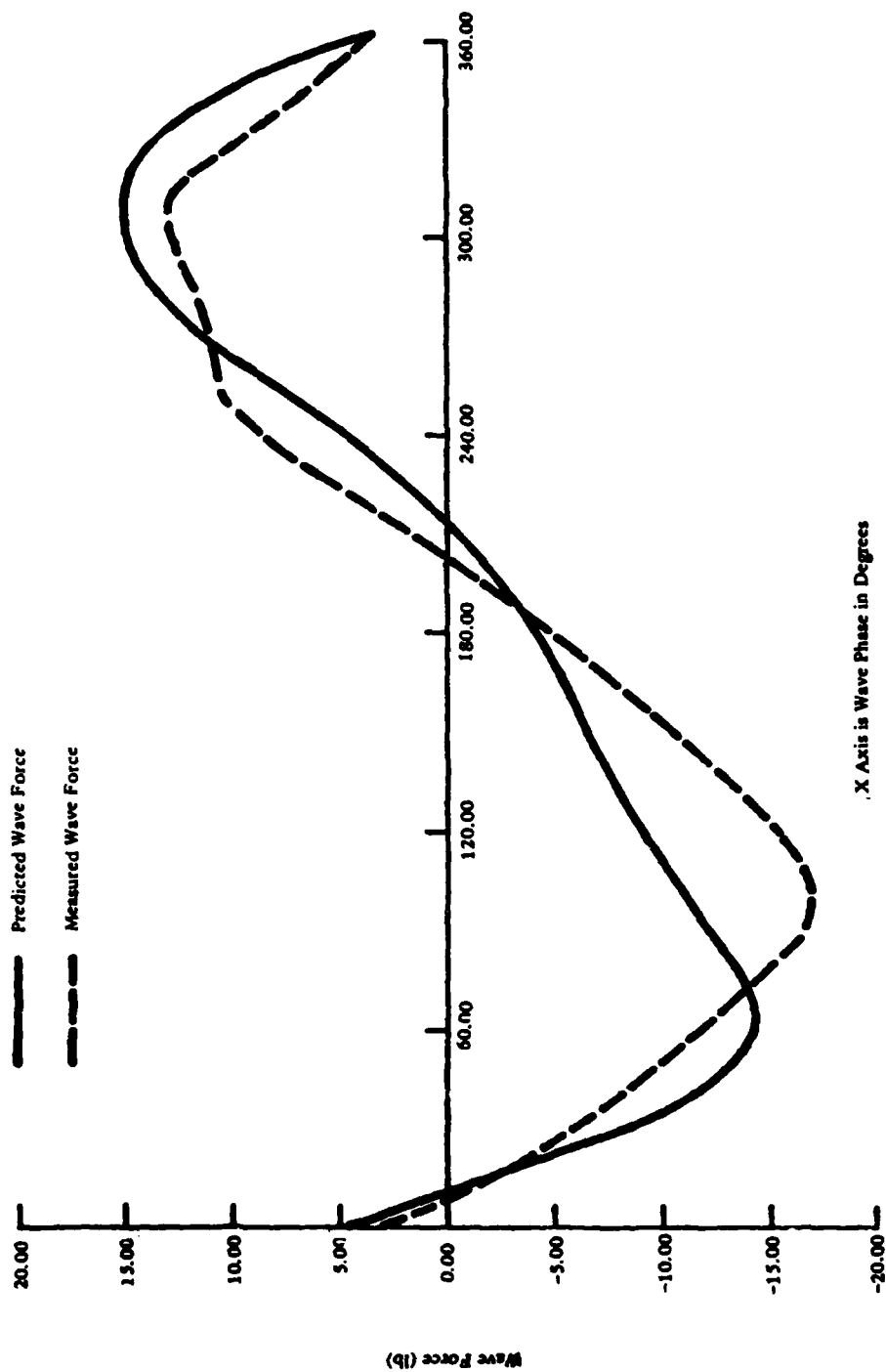


Figure 1. Measured wave force versus predicted wave force for a complete wave cycle of a 4.8-second, 4.3-foot high wave.

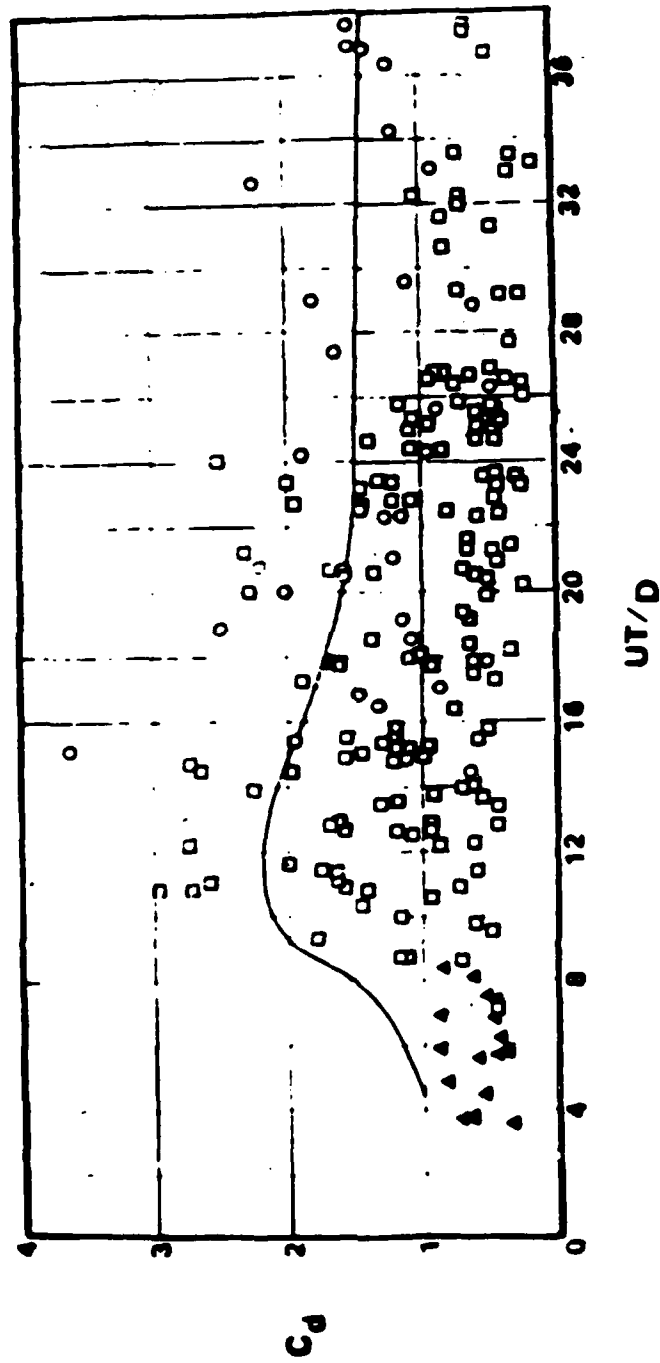


Figure 2. Drag coefficient versus Keulegan-Carpenter number  
(Wiegel 1964).

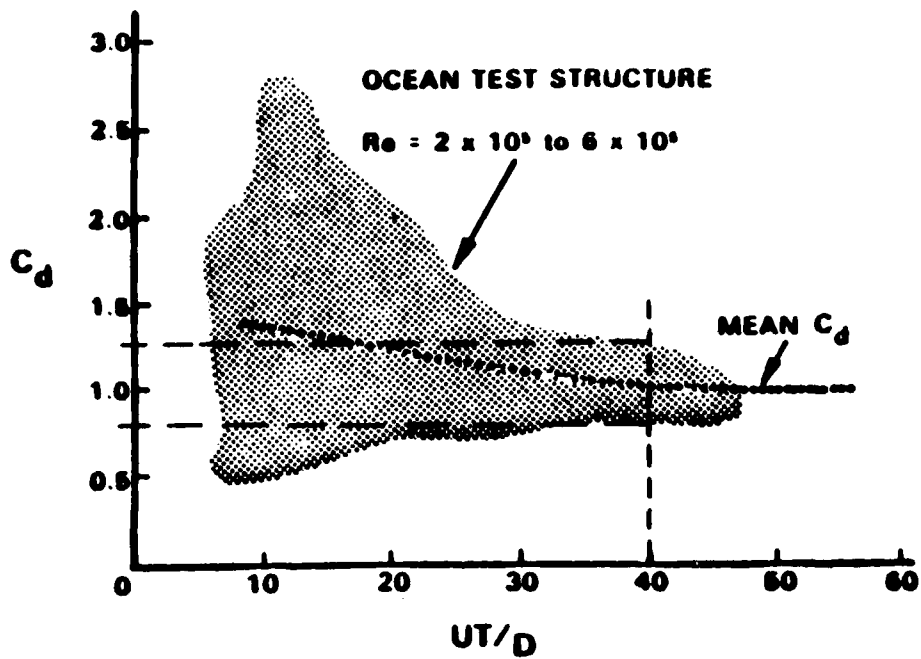


Figure 3. Drag coefficient versus Keulegan-Carpenter number (after Heideman, et al., 1979).



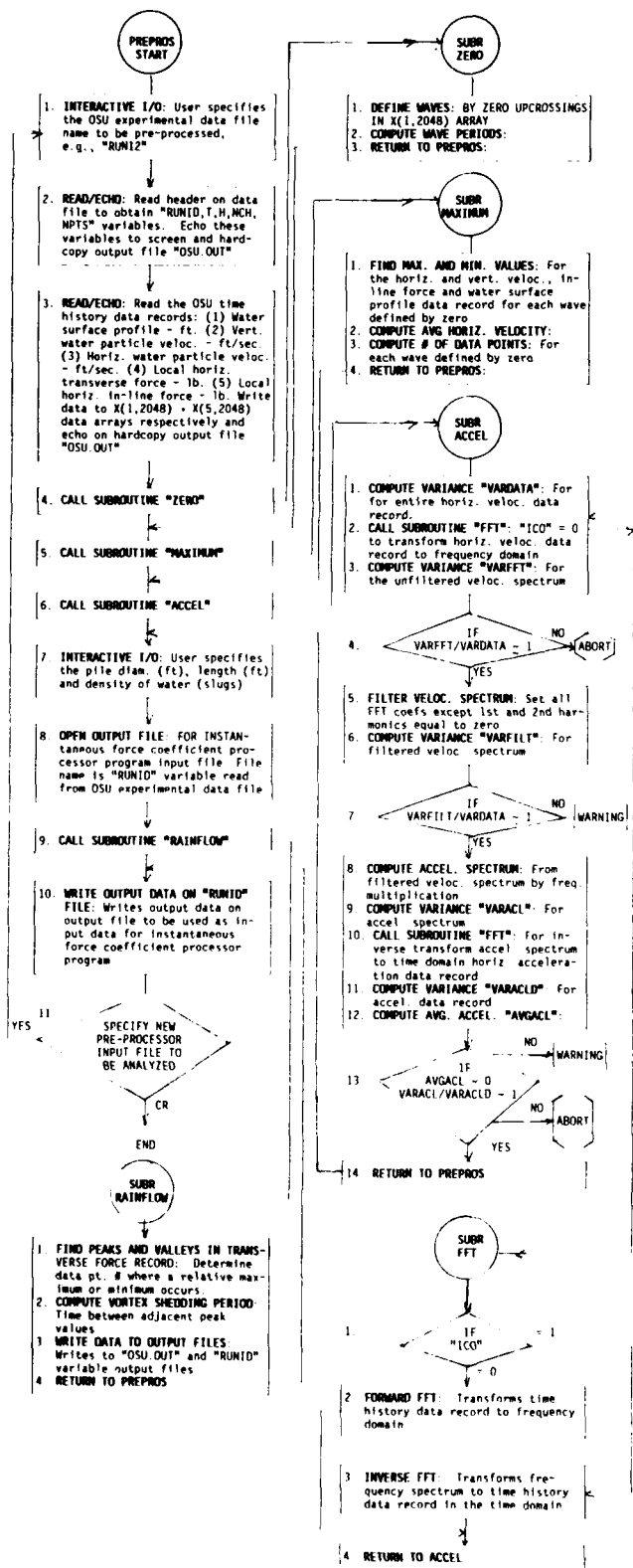


Figure 4. PREPROS flow chart.

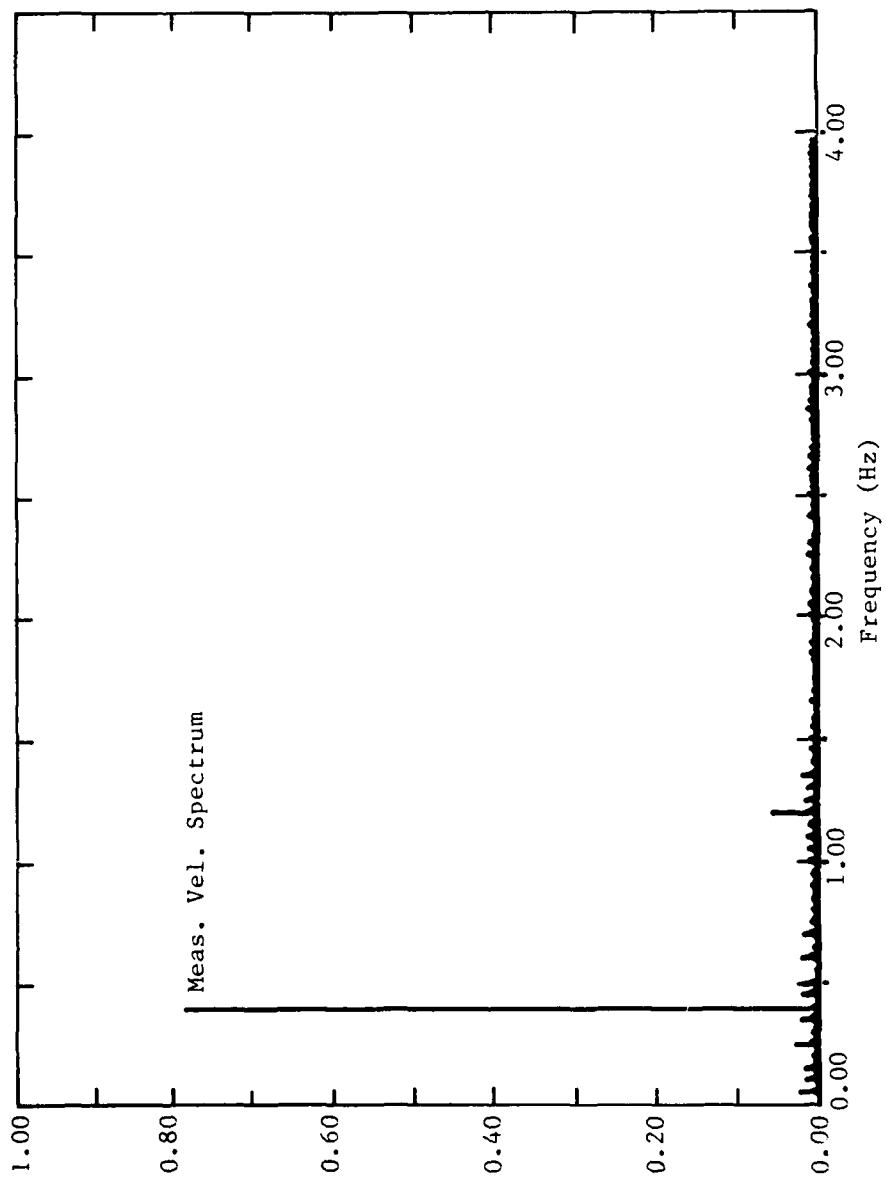


Figure 5. Horizontal water particle velocity amplitude spectrum for approximately 2.5-second monochromatic waves.

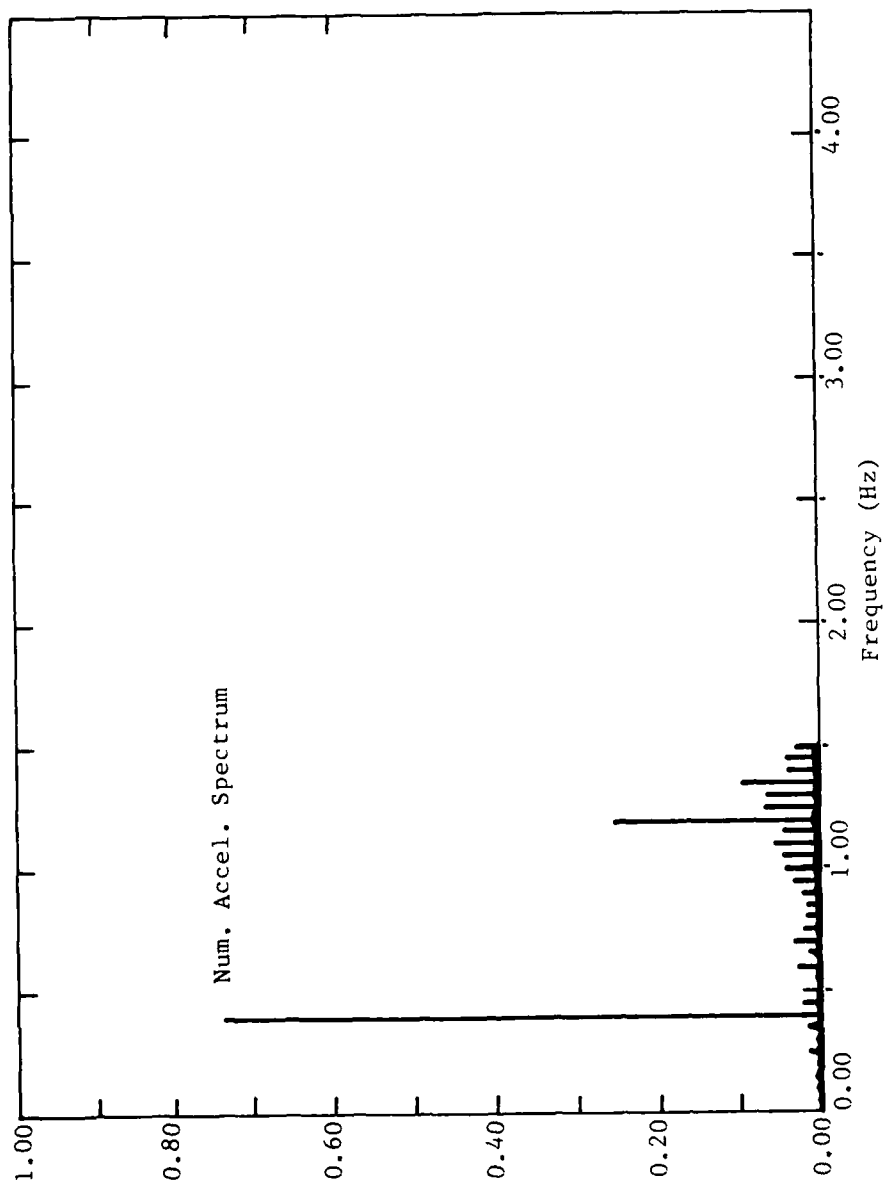


Figure 6. Horizontal water particle acceleration spectrum  
computed from Figure 5 and filtered at 1.5 Hz.

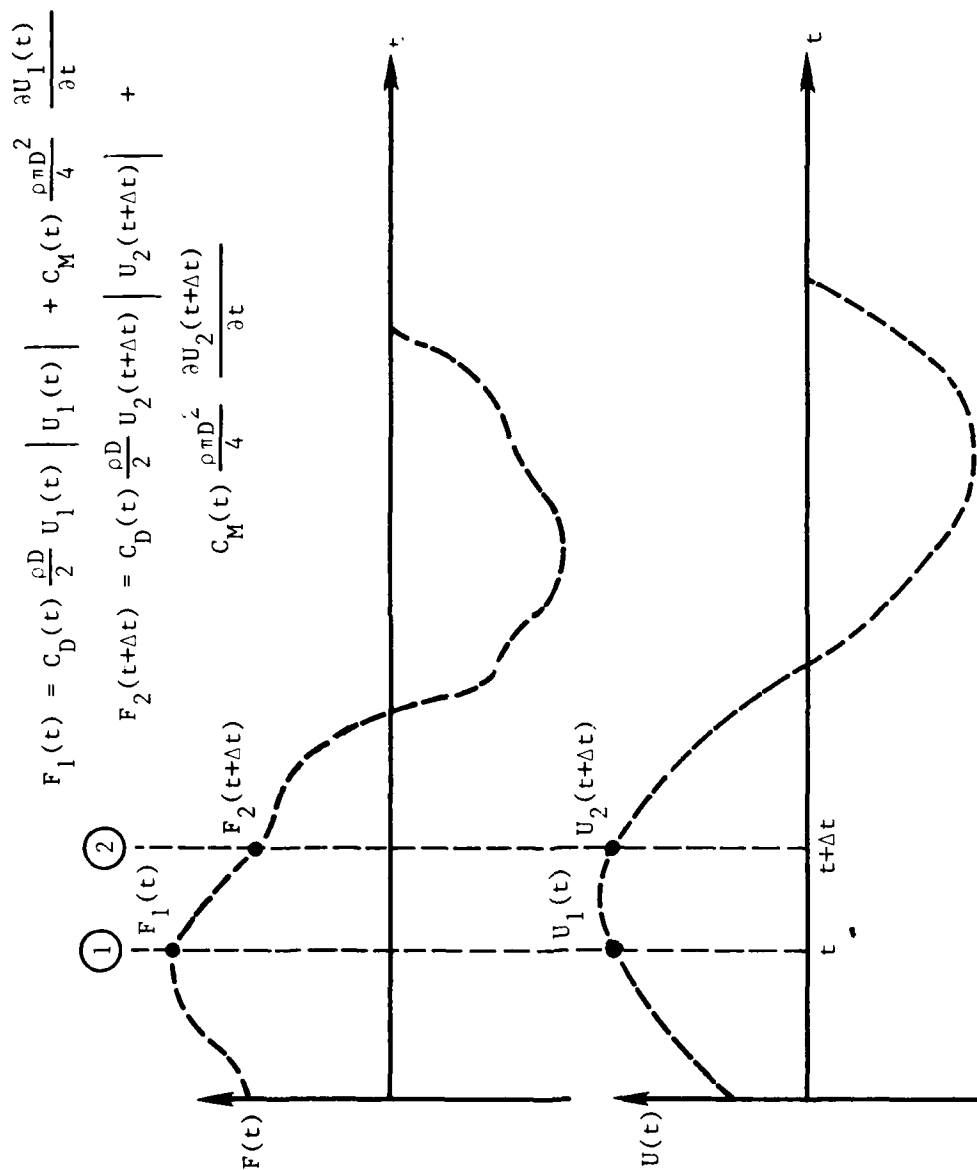


Figure 7. Instantaneous coefficient theory.

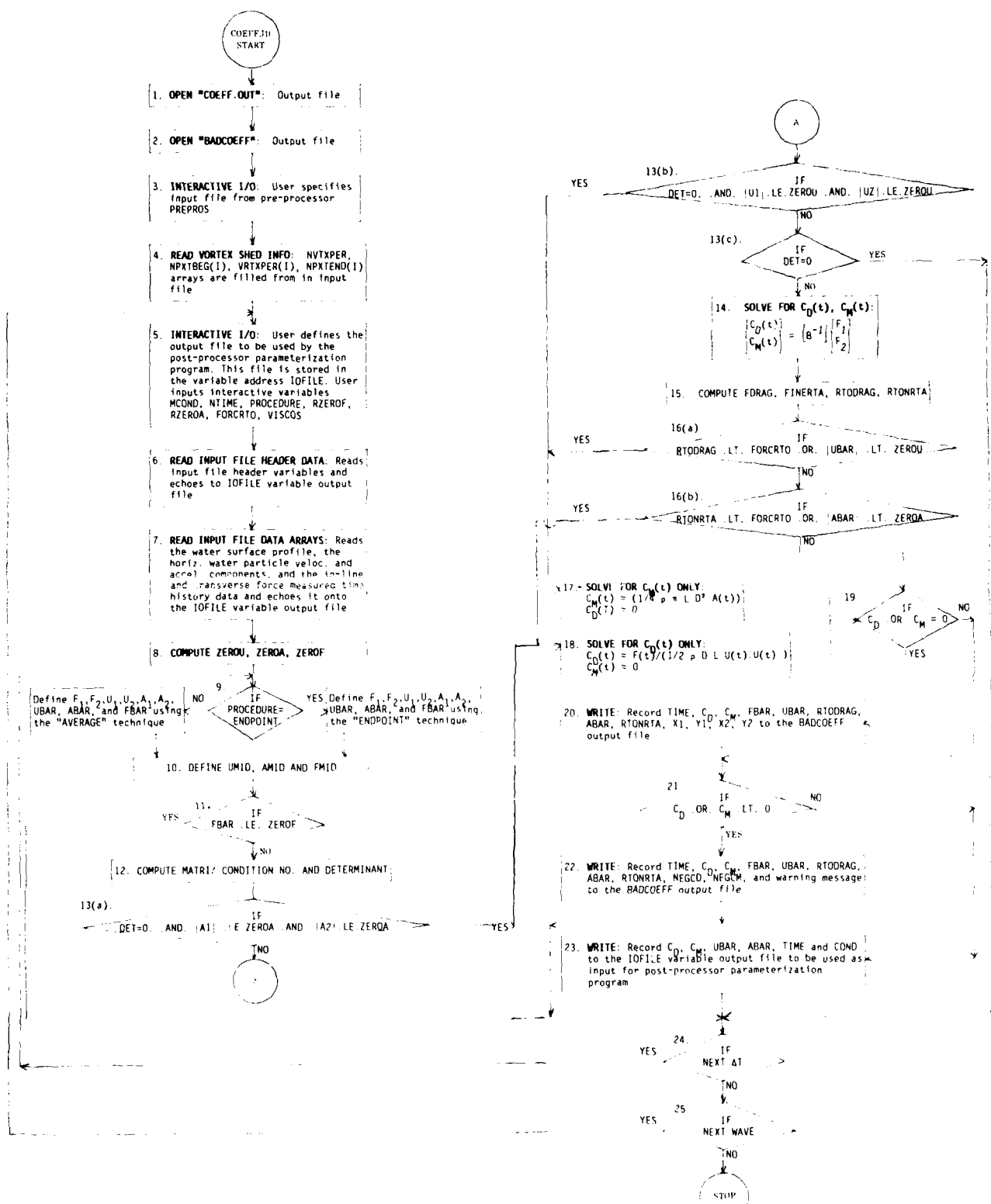


Figure 8. COEFFJD flow chart.

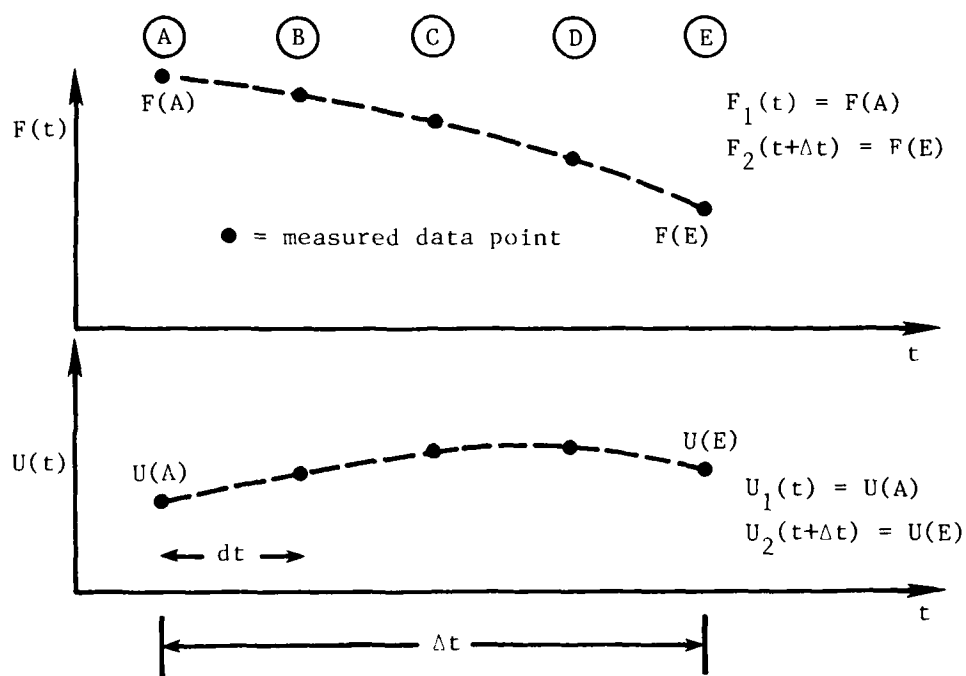


Figure 9a. ENDPPOINT procedure for defining  $U_1(t)$ ,  $U_2(t+\Delta t)$ ,  $F_1(t)$ , and  $F_2(t+\Delta t)$ .

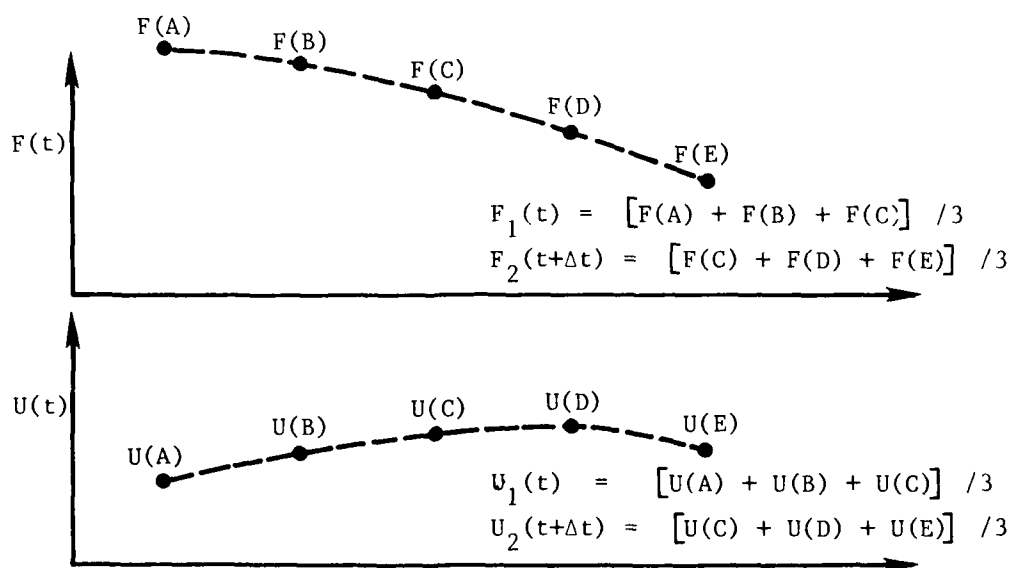


Figure 9b. AVERAGE procedure for defining  $U_1(t)$ ,  $U_2(t+\Delta t)$ ,  $F_1(t)$ , and  $F_2(t+\Delta t)$ .

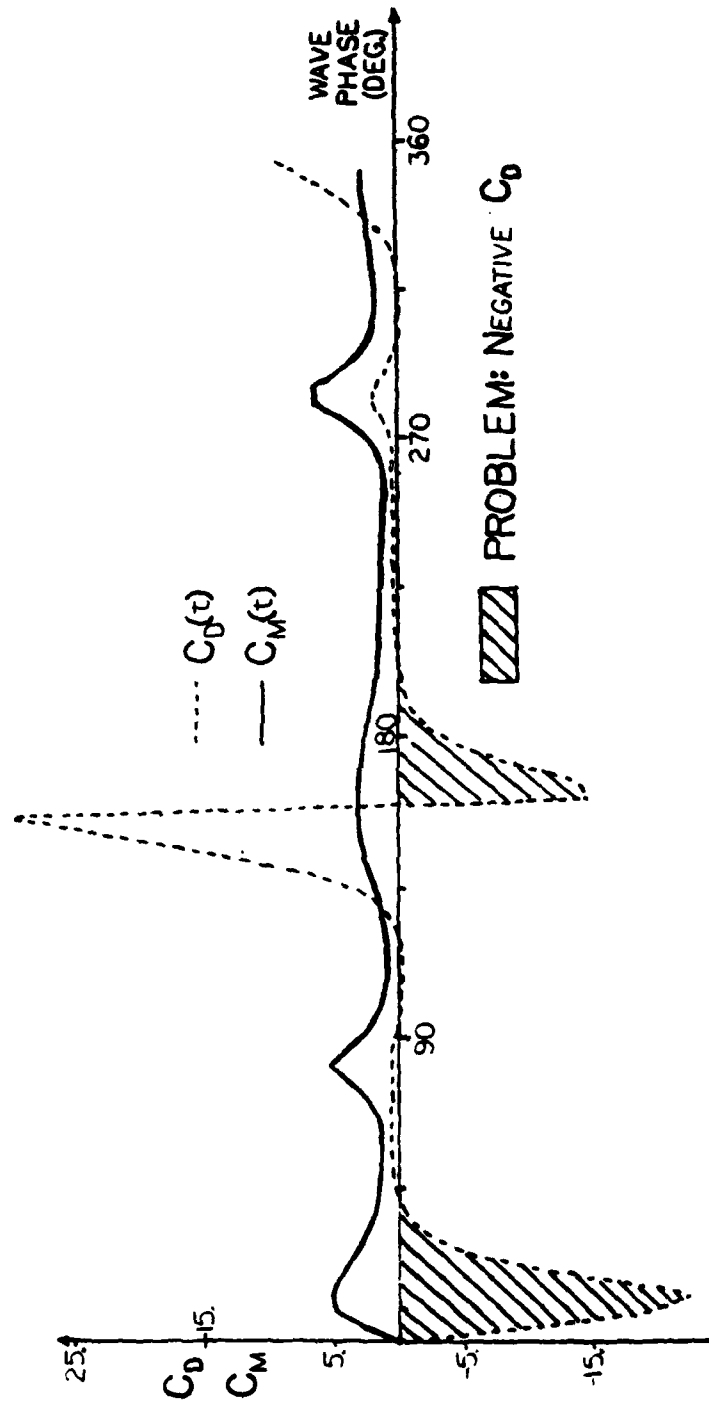


Figure 10. Instantaneous drag and inertia coefficients as a function of wave phase (time).

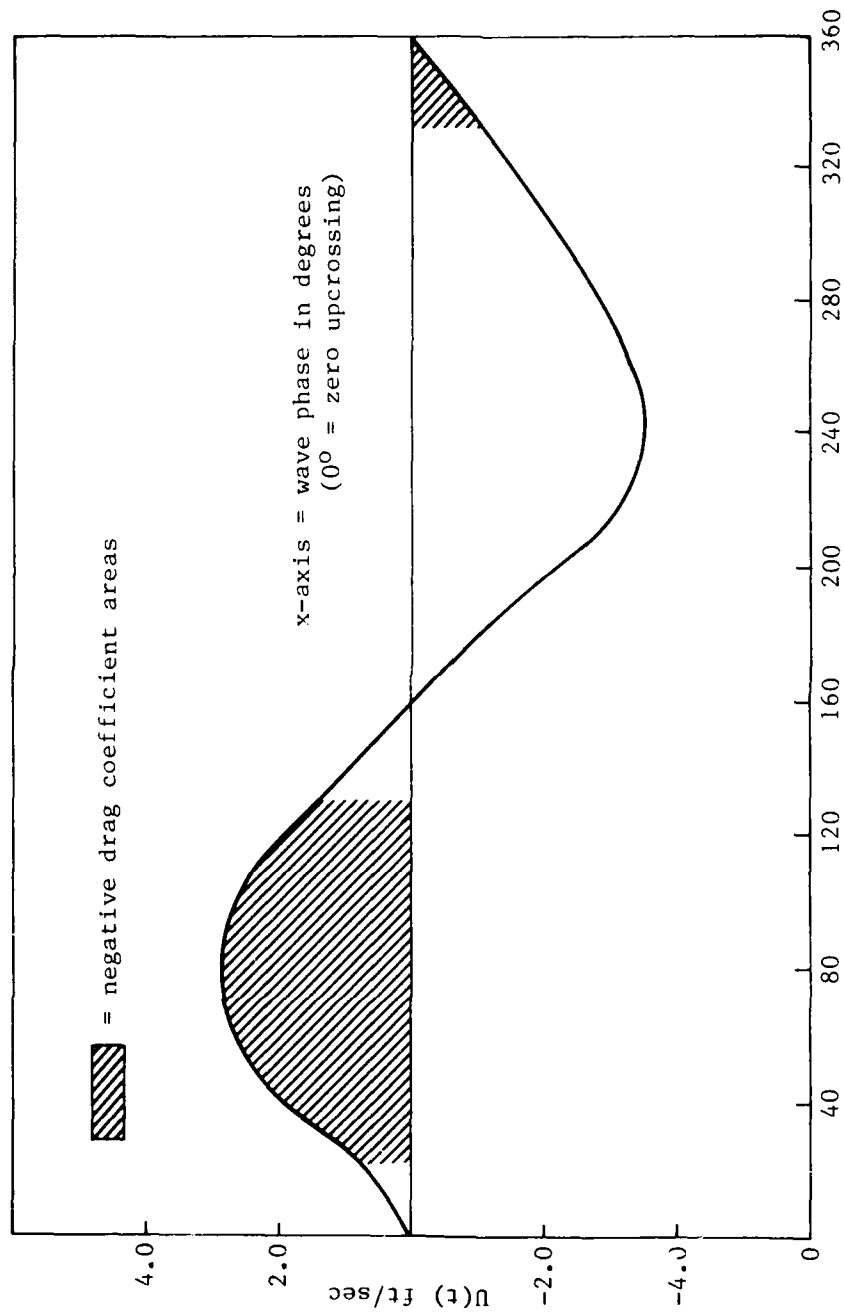


Figure 11. Horizontal water particle velocity time history for a 4.6-second period, 4.3-foot-high wave. Shaded areas correspond to times when negative drag coefficients were computed.



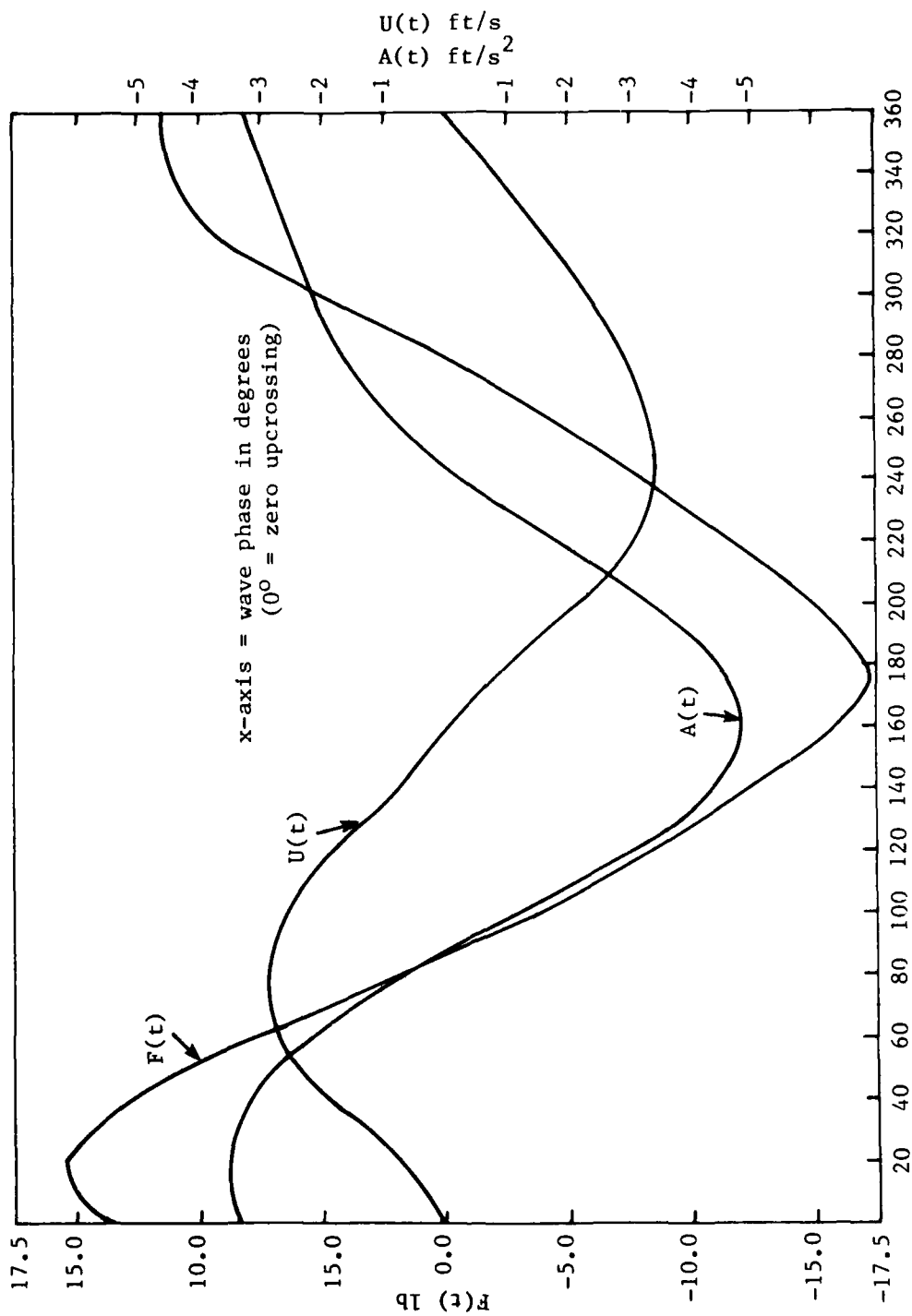


Figure 12. Measured in-line force,  $F(t)$ , velocity  $U(t)$ , and numerically computed acceleration time histories for a 4.6-second period, 4.3-foot-high wave.

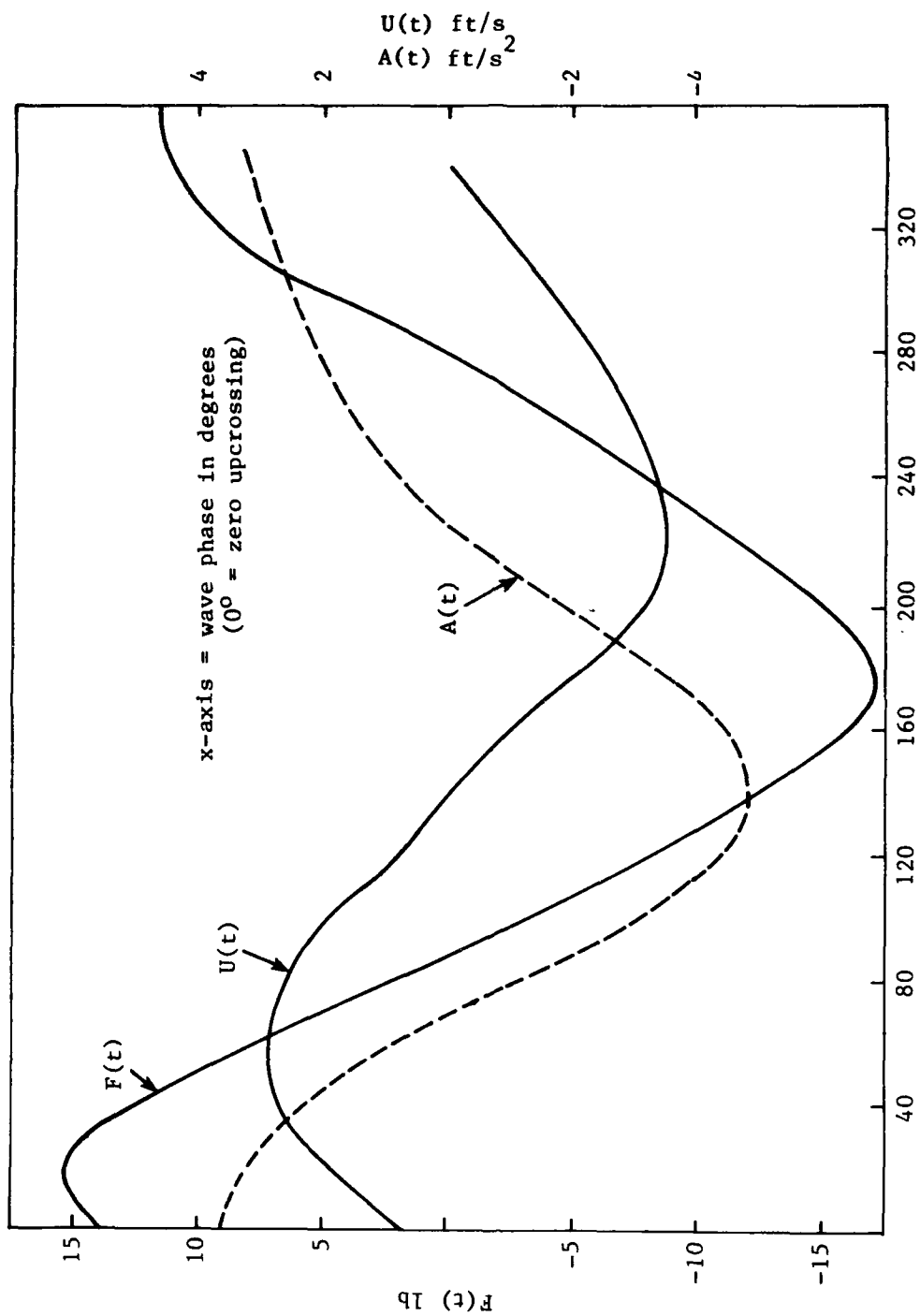


Figure 13. Fictitious in-line force,  $F(t)$ , velocity,  $U(t)$ , and acceleration,  $A(t)$ , time histories obtained by shifting  $U(t)$  and  $A(t)$  of Figure 12 by a  $+20^\circ$  phase shift.

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